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THREE-DIMENSIONAL SHOCK WAVE AND
TURBULENT BOUNDARY LAYER INTERACTIONS

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An extensive experimental study of three-dimensional shock wave turbulent boundary layer interactions caused by shock generators defined solely by angles has been carried out at Mach 3. Sharp fins, sharp swept fins, swept wedges, and semi-cones have been used to generate a wide range of shock waves. The interaction of these waves with turbulent boundary layers has been investigated by surface flow visualization, mean surface static pressure distributions, flowfield surveys of total pressure and yaw, and several flowfield -->

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visualization techniques. Some exploratory high frequency surface pressure measurements have been carried out to evaluate the steadiness of these interactions. Four major new data sets were generated: the flowfield for a 10^{o} sharp fin and $24\text{-}40^{o}$ swept compression corner, surface pressure distributions and surface flow visualization for sharp fins at angles of 12 to 22^{o}, and an extensive set of surface flow visualization tests of wedges up to 24^{o} and swept from 0^{o} to 60^{o}.

Scaling laws for both surface and flowfield features have been derived. Some limited studies were carried out at a Mach number of 2. A flowfield study has shown that the initial part of interactions caused by the same strength and geometrical shock wave generated by different shock generators are all similar. The "footprints" of the interactions, as shown by surface flow visualization, can be categorized as approximately conical or cylindrical, and the boundaries between these two regions have been defined for both Mach 3 and Mach 2. There are still questions with regards to the detailed flowfield structures and physical mechanisms, but the three-dimensional interactions appeared to be less unsteady than that of two-dimensional separated flows.

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TABLE OF CONTENTS

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Scaling laws for both surface and flowfield features have been derived. Some limited studies were carried out at a Mach number of 2. A flowfield study has shown that the initial part of interactions caused by the same strength and geometrical shock wave generated by <u>different</u> shock generators are all similar. The "footprints" of the interactions, as shown by surface flow

visualization, can be categorized as approximately conical or cylindrical, and the boundaries between these two regions have been defined for both Mach 3 and Mach 2. There are still questions with regards to the detailed flowfield structures and physical mechanisms, but the three-dimensional interactions appeared to be less unsteady than that of two-dimensional separated flows.

I. INTRODUCTION

The subject contract covered a 3-year experimental and analytic program in the Gas Dynamics Laboratory at Princeton University. The facilities and instrumentation, the primary experimental tools of the present investigation, were developed under previous OSR support and were expanded, up-graded, and modified during the present program. The extensive results of the study have been documented in detail in a series of reports and publications and presented at many national and international meetings. The present report is a brief overall summary of the activity under the subject contract, year-by-year, which led to significant advances of our understanding of the complex interaction of a shock wave and a turbulent boundary layer. In the following sections the report details the overall objectives of the program and the yearly programs which were designed to meet the overall goals of the subject contract. The general conclusions of the present study are summarized, a brief report is given on the staff and students that were involved in the program, and the significant scientific interactions which took place are noted.

II. OVERALL OBJECTIVES AND WORK STATEMENT

Previous studies which explored two-dimensional and three-dimensional interactions of shock waves and turbulent boundary layers provided the basis for the subject research program. The early work revealed many new features and the exploratory studies of several geometries began to reveal some of the underlying physics. There appeared to be similarities in the interactions generated by geometries which had no specific dimension, that is, models which could be defined soley by angles. The subject experimental research program had the goal of achieving a better understanding of the overall scaling and flowfield structure of this class of three-dimensional shock wave turbulent boundary layer interactions. The interactions were generated by three experimental geometries designated the "sharp-fin", "the swept sharp-fin", and the "swept compression corner," with the semi-cone added late in the program, Fig. 1. The specific tasks posed in the original work statement were:

1) examine the overall scaling of these interactions in terms of shock strength, sweepback angle, geometry, and other pertinent parameters.

2) perform experiments designed to reveal the Mach number effect on the interaction scaling.

3) based on the results of these experiments and analyses, attempt to construct an overall scaling framework which relates the characteristics of the individual interactions.

4) by means of appropriate flowfield surveys and flow visualization, examine the physical mechanisms and flowfield structures which lead to the observed overall scaling behavior.

As the research progressed with the three original configurations, the fourth geometry, a semi-cone was added as a specific test of some of the new concepts of conical similarity. The study of blunted fins, a geometry with a geometrical dimension, which had been studied under previous OSR support, was separated out as not being part of the class studied. This work was continued under separate Navy support.

The original contacts with computations, primarily carried out with Dr. C. C. Horstman of NASA-Ames, was expanded considerably in the latter phases of the present program with the inclusion of Prof. D. Knight of Rutgers. Although the involvement with computation was not part of the original goals, it became an important element in the subject program. The cooperation provided a key element of computational validation and a source for new insights into the flowfield which could not be obtained directly in the present program.

III. YEARLY PROGRAMS

The overall objectives of the subject contract were used to lay out specific yearly tasks, formulated to build a structure for the overall program which would provide the basis for the final resolution of the problems tackled. In the following sections the yearly objectives, a brief summary of the work accomplished, and a brief review of the detailed work carried out during each of the contract years is presented.

1. Yearly Research Objectives

a) 1981-82

The research objectives for the 1981-82 contract year were:

1) continue to reduce, analyze, and correlate existing data base,

2) design, fabricate, install, and calibrate a new, lower Mach number nozzle for the 20 x 20 cm High Reynolds Number Tunnel,

3) develop and use flow visualization techniques suitable for high-speed 3D turbulent flows,

4) use the computer-controlled "cobra" yaw probe to investigate the flowfield of a sweptback compression corner,

5) conduct tests and analyses aimed at defining the boundary of cylindrical and conical flow symmetry in 3D swept corner flows at Mach 3,

6) build the data base at Mach 3 in certain important areas, including surface pressure measurements, using the swept fin.

b) <u>1982-83</u>

The research objectives for the 1982-83 contract year were:

1) examine the applicability of the classical "independence principle" for the scaling of swept cylindrical shock/boundary layer interactions,

2) evaluate the applicability of the established Reynolds number scaling law for 3D interaction surface features to interaction <u>flowfields</u> as well,

3) perform 2D compression corner experiments at Mach 2 as a first step in extending the Reynolds number scaling law to variable Mach number conditions,

4) expand the Mach 2 experimental data base for both fins and swept compression corners,

5) find the cylindrical/conical flow regime boundary at Mach 2 and combine this with previous Mach 3 results in order to gain further insight on the physics of the phenomenon,

6) begin the formulation of an overall scaling scheme for non-dimensional 3D interactions generated by geometrically dissimilar shock generators.

c) <u>1983-84</u>

The research objectives for 1983-84 contract year were:

1) with the addition of the semi-cone, consider the overall

similarity conditions for conical shock wave turbulent boundary layer interactions.

2) extend the sharp fin studies to higher angles to provide an extended cross-check of strong shock interactions generated by the wedge studies.

3) initiate a review of the work carried out under the present and previous contracts to integrate surface flow visualization, pressure distributions, and flowfields, in the light of the concepts of separation and reattachment, conical and cylindrical flows, and to provide the first basis for the studies of steadiness,

4) expand the interactions with the computational groups at NASA-Ames and Rutgers,

5) initiate the initial high frequency studies to determine the steadiness of the three-dimensional interactions which are the primary subject of the current contract, these studies to include hot-wire and high frequency surface static pressure measurements.

2. Summary of Work Accomplished

A brief summary of the work accomplished during each of the contract years is noted below:

a) 1981-82

Progress during the 1981-82 contract year included the experimental definition of cylindrical and conical flow regimes

in interactions generated by swept compression corners at Mach 3, and a tentative physical explanation of these phenomena. A parallel study of interactions generated by sweptback fins indicated conical interaction symmetry. The character of flow unsteadiness at the beginning of a separated shock/boundary layer interaction was studied and was found to be of greater importance than was generally thought. The experimental testing capability was extended through the fabrication and calibration of a Mach 2 nozzle and the use of a computer-controlled auto-nulling yaw probe. An initial study of three-dimensional high-speed flow visualization uncovered several promising new techniques. Finally, cooperative efforts were initiated with other investigators who had developed computational methods to predict flows of the type under investigation.

b 1982-83

Progress during the 1982-83 contract year included an experimental test of the "independence principle" applied to swept cylindrical interactions. Two major experimental flowfield survey programs proved that the Reynolds number scaling law previously developed for 3D interaction surface features holds for the corresponding flowfields as well. A series of 2D interaction experiments at Mach 2 were carried out as the first step in extending this scaling philosophy to variable Mach number. Also at Mach 2, the swept compression corner cylindrical/conical flow regime boundary was found and compared

to previous Mach 3 results. The Mach 2 studies, although limited, were used to explore the general extension of the Mach 3 results to lower Mach numbers. Although the scaling results are similar, the coefficients of the derived empirical laws for Mach 2 are significantly different, and the general use of the scaling parameters requires broader Mach number variation to substantiate variable Mach number predictions. Finally, a "conical similarity" hypothesis was proposed as a means of correlating and understanding the behavior of interactions produced by geometrically dissimilar shock generators. Additional experiments using fin, swept corner, and semicone shock generators lent strong support to this hypothesis. Detailed interactions with the computational activities at Ames and Rutgers were continued with interchanges of data and computational results and consultation on specific tests and computations for the future.

c) 1983-84

The main emphasis was on the concepts of similarity conditions which integrated the studies of fins, wedges, and cones. It was found that the interaction characteristics depend primarily on the inviscid shock wave strength and shape, and conical similarity was found for disparate shock generators. A significant effort was expended in expanding the data base for sharp fins. With the extensive swept wedge studies, the shock strengths generated varied over a much wider range than those

available from the fin results. A new model and test program have extended the fin results to as high as 22°, providing the base for an extended study of strong shocks generated by this geometry. The range from 12° to 22° reveals the development and then disappearance of a feature called "secondary separation" for tests with thin boundary layers. This phenomena was not found for the thick boundary layer case. A critical review was initiated in an attempt to integrate the significant data sets which have been generated recently with the previous work and, in particular, to focus on questions of separation, conical/cylindrical boundaries, and steadiness. There are still unanswered questions regarding the concepts of separation, and the definitive conclusions can not yet be supported by the data base. The concept of a rather sharp division between conical and cylindrical flows, as previously suggested, has been re-examined in detail. Although there appears to be regions in which the flow is approximately conical or cylindrical, the boundary between the two regions is not as sharply defined as previously proposed. The lack of specific data available to evaluate steadiness of the flow required the development of a new program in that area. Initial results were obtained using hot-wires and high frequency surfac presure gauges which indicated that the three-dimensional flows under consideration were unsteady, but they appeared to be considerably more steady than two-dimensional separated flows. The flowfield scaling predicted by experiment has now been

compared with a series of computational studies covering a fairly wide range of geometries. Generally, upstream influence predictions are reasonably close to experiment, deviating somewhat at high sweep angles.

3. Brief Progress Reviews

In the following sections we briefly review the progress made each year in support of the research objectives.

a) Progress during 1981 82

1) Conical and Cylindrical Flows: Existing Data Base and New Experiments

Our initial exploratory work with sweptback compression corners (carried out under AFOSR sponsorship in 1979 and 1980) revealed the existence of both cylindrical and conical 3D shock/boundary layer interaction regimes. The limited investigations prior to this time had shown some evidence of such regimes, but no single study had previously revealed the fact that both are possible within the parametric variation of a single experimental geometry. One of our major goals was to understand how and why it happens, so as to gain a better grasp of the overall scaling rules which govern 3D interactions in general. The existence of either conical or cylindrical symmetry offered the possibility of a powerful simplification of 3D interaction scaling, i.e., that one of the three space dimensions might be degenerate, so that quasi-two-dimensional (2D) scaling

might apply. It would then be necessary only to know the form of the quasi-2D scaling rules and the boundary between cylindrical and conical regimes.

While the appropriate quasi-2D scaling rules were still subject to ongoing study, a possible "breakthrough" in understanding the cylindrical/conical boundary was made by examining the existig matrix of parametric swept corner experiments in α-λ coordinates, where α is the streamwise compression corner angle and λ is the sweepback angle (see Fig. 4). We developed experimental criteria with which to judge whether a given swept corner interaction was asymptotically cylindrical or conical. Plotting these points in α-λ space, a rough outline of the cylindrical/conical boundary appeared. We then carried out experiments for additional α-λ combinations in order to define this boundary with an accuracy of about $\pm 3°$ in λ (see Fig. 2). We noticed a similarity between the observed flow regimes boundary and the conditions for inviscid shock wave detachment from the swept compression corner. Inviscid detachment appeared to approximate the asymptotic shape of the interaction , subject to two conditions of interpretation: 1) that the "effective" detachment Mach number in the boundary layer is less than that in the freestream, and 2) that, for sufficiently high α and low λ, no practical experiment can be done without the effects of finite model geometry becoming important.

2) Mach 2.0 Experimental Capability

In order to assess the effect of Mach number on 3D shock/turbulent boundary layer interactions, we designed, built, and calibrated a Mach 2 nozzle for our high-Reynolds number test facility. The results of the calibration revealed that the new nozzle is successful in providing a clean Mach 2 freestream but the wall boundary layer was not as uniform as required for our tests. The pitot traverse along the centerline of the test section showed no flow disturbances other than weak waves from the nozzle exit, window plugs, etc. The mean Mach number was found to be 1.95. The turbulent boundary layer on a flat plate installed in the test section was surveyed extensively and exhibited the expected wall-wake criteria for equilibrium. Figure 3 illustrates the boundary layer growth in the streamwise direction. The results define the incoming conditions for 3D interaction studies to be carried out at Mach 2 during the following contract year.

3) 3D Flow Visualization

Recognizing that the inability to visualize complex 3D flows at high speeds was a major stumbling block to our work and that of others, we initiated a research effort to develop new techniques for that purpose. A number of potentially promising concepts were tested at Mach 3 and high Reynolds numbers. Five of these gave useful results which were put to general use in our research program where appropriate.

One of the most useful of these techniques, as illustrated in Figs. 4 and 5, is the "local vapor screen." Instead of attempting the complex procedure of seeding the entire wind tunnel flow with an aerosol, we inject a volatile liquid only through a suitable orifice in the immediate flow region of interest. The action of boiling and turbulent unsteadiness creates a local "fog" from this injectant, which is rendered visible by appropriate lighting.

All of the flow visualization techniques which proved successful have been made available to the research community in a publication by Settles and Teng. Meanwhile, our flow visualization development continued with emphasis on high-speed photography.

4) "Cobra" Probe Surveys

The automated "cobra" probe for 3D flowfield yaw surveys was completed and tested during the previous contract year. This year we began to use it to obtain data on the flowfield structures of 3D interactions. The initial experiments were done using the swept corner geometry at Mach 3, which is depicted in Fig. 4. However, we chose the swept shock interaction generated by a sharp-leading-edge fin for the first major test using this new flowfield diagnostic instrument.

The swept shock interaction, as diagrammed in Fig. 6, takes place both on the tunnel floor and on a flat plate, yielding a difference in incoming turbulent boundary layer thickness of

about 3:1. Our previous work under AFOSR support has shown that its "footprint", when scaled by δ_o, varies as $Re_{\delta_o}^{1/3}$ at Mach 3. The question of whether or not the entire <u>flowfield</u> also follows this scaling rule was an important one which the experiments addressed. Specifically, we chose survey planes at appropriate distances, Z, from the fin leading edge, according to the above scaling rule, for both the flat plate and tunnel wall interactions with $\alpha_s = 10^\circ$. We then carried out detailed flowfield surveys in both cases using the automated cobra probe.

Typical results of these surveys are illustrated in Figs. 7 and 8, which depict maps of both pitot pressure and yaw angle contours for the tunnel wall case. The crux of the experiment involved comparing the survey results for the tunnel wall and flat plate, scaled appropriately, to determine whether or not the previously established scaling law was effective for flowfield as well as "footprint" shape and size. Preliminary indications were that the scaling law was successful in the interaction flowfield.

5) <u>Data Base Extension: Swept Fin Geometry</u>

Additional surface pressure measurements were made to extend the current Mach 3 data base for the case of the swept fin geometry. An example of these measurements is shown in Fig. 9. Depicted in this figure are streamwise surface pressure distributions at various distances spanwise from a swept fin

with 55° leading-edge sweepback angle. After an initial "inception length" from the leading edge, the length scale of these distributions was observed to grow almost linearly with spanwise distance y. By finding a virtual origin for this growth (denoted by Δy) we collapsed pressure distributions at various spanwise distances onto a common curve in <u>conical coordinates</u>, as shown. This illustrated that the swept fin interaction in question obeyed a quasi-conical symmetry. This result is consistent with the previous symmetry arguments stated for swept compression corners.

In addition to support from the subject contract, the swept fin experiments were partially funded by Grant NAG-2-109 from NASA-Ames Research Center.

6) <u>Wall Pressure Fluctuations</u>

High-frequency-response Kulite pressure transducers were used to obtain time-resolved measurements of the surface pressure near the beginning of the two-dimensional 24° compression corner flowfield illustrated in Fig. 10. The rationale for this experiment arose from earlier tests in which it was found that the three-dimensional separated flow ahead of a blunt fin was unsteady. The question then arose concerning the steadiness of a nominally 2D interaction. The results showed that large-amplitude pressure fluctuations exist near the beginning of the interaction in the region where the mean wall pressure rises rapidly. There is a strong indication that the flow in

this region is dominated by an unsteady shock wave structure undergoing random streamwise excursions on the order of the incoming boundary layer thickness. Thus, the familiar shape of the mean wall pressure-rise is actually due to the superposition of intermittent, high amplitude, shock-induced fluctuations on the pressure signal of the undisturbed incoming boundary layer. This phenomenon is illustrated by pressure-time histories at three selected points near the beginning of the interaction in Fig. 11.

These results have some important implications: numerical solutions of the Navier-Stokes equations for such interactions generally do not account for such high-frequency unsteadiness, so that an important physical mechanism may be overlooked in these solutions. It is clear that mean wall pressure distributions and surface streak patterns display some type of average of the fluctuating flow, but the nature of this average is unclear. Thus the proper interpretation of such mean measurements is somewhat clouded. This subject clearly deserves additional study and must also be considered in the three-dimensional cases.

This work was supported primarily by Contract N60921-82-K-0064 from the Naval Air Systems Command. However, the development of the high-frequency Kulite cell and data acquisition and reduction capability has been under AFOSR support as a necessary capability for the three-dimensional work to follow.

b) Progress during 1982-83

1) A Test of the "Independence Principle" in Swept Cylindrical Interactions

Our past research had shown that cylindrical interactions, in which the interaction scale becomes constant with respect to the spanwise dimension, comprised an important 3D interaction flow regime. It is this regime which bridges the gap between two-dimensional (2D) and conical (3D) shock-induced flows. Further, our previous work had identified both the cylindrical-conical regime boundary at Mach 3, and the probable physical explanation of its occurrence. We approached this problem using the classical notion of quasi-2D flow. Since one of the three space dimensions is degenerate for cylindrical interactions, one may begin by assuming that the flow in any plane normal to the cylindrical axis of symmetry is identical to an "equivalent" 2D flow. This assumption has been termed the "independence principle," since it requires that flows in the normal and crossflow directions be independent of one another. It was reasoned by early investigators that the independence principle could not hold for turbulent flows at any speed, since the inherent nonlinear 3D nature of turbulence precludes a simple decoupling of normal and spanwise flows.

Thus, even though there is good reason to doubt a simple applicability of the independence principle to cylindrical 3D interactions, a proper experimental test of the principle has

never been made in such flows. We have been able to carry out a rigorous test of the independence principle as outlined above. It required, in addition to our extensive data set on swept 3D interactions, a knowledge of how the 2D interaction scale varies with Mach number. This was obtained from the comprehensive experimental data of Roshko and Thomke (AIAA J., July 1976). We were able to recast their experimental data correlation form in a way that reveals both Mach and Reynolds number effects explicitly as a function of compression corner angle, α.

Comparing the 2D and cylindrical 3D results, at the same normal Mach number, is shown in Figs. 12a and 12b. As one might expect, the crossflow coupling is negligible at small sweepback angles. The independence principle thus holds within the data accuracy for sweepback angles up to 10° - 20°, beyond which it fails progressively.

Finally, one may assume quasi-2D flow for the entire range of swept cylindrical interactions if an appropriate "crossflow correction" can be found to remove the progressive failure of the independence principle with increasing sweepback angle, λ . Such a correction,

$$1/(1 + K \tan^2\lambda)^{\frac{1}{2}} ,$$

was suggested by Prof. George Inger, based on his ongoing research concerning the 3D law-of-the-wall and eddy viscosity.

As shown in Fig. 13, an empirical value of K = 4 in this correction succeeds in accounting for crossflow coupling, thus permitting the general applicability of the quasi-2D assumption. While this correction term suggests that crossflow coupling is a purely geometrical function, our research is continuing to search for its complete physical meaning.

2) Reynolds Number Scaling of 3D Interaction Flowfields

Our previous AFOSR-supported research led to a scaling law for Reynolds number effects on 3D interactions. We were able to demonstrate the generality of this scaling law in that it described both fin- and swept-corner-generated interactions at Mach 3. However, this demonstration had been made only for the surface features of these interactions (static pressures, streak angles, etc.). A more rigorous test including the entire flowfield was required. A sharp-leading-edge fin at 10° angle of attack was tested with two different equilibrium incoming boundary layers. Detailed yaw angle and pitot surveys were made under both test conditions in order to map the respective interaction flowfields. The major point of these experiments was to correlate the flowfield maps of the two interactions using the Reynolds number scaling law previously derived based on surface measurements.

As illustrated by Fig. 14, the experimental results generally support this concept. In X and Z coordinates, scaled

according to the established Reynolds number law, the thin and thick boundary layer interactions exhibit a close similarity of mean pitot pressure contours (PT). The Reynolds number scaling law is shown to hold reasonably well for flowfields as well as surface interaction features.

A series of flowfield surveys similar to those described above for the $\alpha = 10°$ fin interaction were also carried out for one swept compression corner interaction described by angles $\alpha = 24°$ and $\lambda = 40°$. Cobra probe surveys were made with two incoming turbulent boundary layer thicknesses. The purpose of these experiments was twofold. First, it was desired to check the applicability of the established Reynolds number scaling law to the flowfield features of an additional important interaction class. Second, these measurements would provide the first quantitative data on swept corner interaction flowfield features. From them we hoped to gain insight into the physical nature of conical 3D corner flows.

Concerning the scaling law check, the results are illustrated in Fig. 15. Here the significant flowfield features (separation shock, coalesced shock, and slip line) are shown in scaled coordinates for both the thin and thick incoming boundary layers. The comparison between the two is excellent, lending further credibility to the established scaling law as a proper representation of Reynolds number effects on 3D interactions.

These results have been analyzed in detail in an MSE Thesis by Mr. T. M. McKenzie.

The flowfield data for the 24-40° swept corner interaction provided an important new test case for computational solutions of the Navier-Stokes equations. In his cooperative AFOSR-sponsored research program, Prof. Knight of Rutgers discussed his plans to begin swept corner computations and Dr. C. C. Horstman of NASA-Ames Research Center has computed the 24-40° case. The outcome of these computational efforts and their comparison with the experiment provided important new information, since the 24-40° swept corner interaction is 2 to 3 times stronger (in terms of shock pressure ratio) than the strongest sharp fin-generated interaction which had been computationally modeled thus far.

3. 2D Compression Corner Experiments at Mach 2

What has been learned about 3D interactions owed much to our prior knowledge of related 2D interactions. This knowledge was instrumental, for example, in our derivation of a general Reynolds number scaling law. A first step in our Mach 2 experiments was to determine the behavior and range of the Reynolds number scaling exponent, n. The Mach 2 results, with an average value of n = -1/2, were quite similar to that previously observed at Mach 3, except that n = -1/3 in the latter case. This indicates that the Re_δ residual scaling effect was stronger at the lower Mach number, which remains to be explained on a

physical basis through further research and analysis. It also provides a basis with which to extend the present scaling philosophy to general 3D interactions at Mach 2.

4) Sharp Fin Experiments at Mach 2

A second phase of our initial Mach 2 experiments involved exploratory tests of sharp fin and swept corner interactions. These experiments were exploratory in the sense that they were designed to provide an initial look at the possible interaction regimes at the new Mach number, and also to discover the limits of shock generator size and shape within which tunnel stalling could be avoided. Fin angles of attack above 8° were not possible to run, at least with the original model and test section configuration, due to blockage generated by the strong shock wave/sidewall boundary layer interaction. Both surface flow visualization traces and surface pressure distributions were taken for the available test conditions. The results of these tests, and limited 2D compression corner tests using the Mach 2 tunnel floor boundary layer, indicated the problems with the two-dimensionality of that layer and the study was discontinued.

Similar fin interaction experiments were carried out using a flat plate boundary layer at Mach 2, which has proved to be two-dimensional. Again, blockage prevented any tests at a fin angle of attack greater than 8°.

5) Swept Corner Cylindrical/Conical Boundary at Mach 2

An appropriate selection of models from our swept compression corner test matrix was also tested at Mach 2. The experimental surface flow pattern and static pressure data revealed the same two interaction regimes already observed at Mach 3, namely, cylindrical and conical flow. However, the boundary between the two regimes, while having roughly the same shape as at Mach 3, lies significantly lower in terms of the sweepback angle, λ. This result is consistent with our physical interpretation of the cylindrical-conical boundary in terms of invisid shock wave detachment.

The cylindrical/conical flow regime boundary at Mach 2 is shown in Fig. 16. These results reveal that the boundary is approximated by an inviscid shock detachment line, as was the case at Mach 3. However, the Mach number characterizing this detachment line (1.85) is not significantly less than the freestream Mach number (1.95). This contrasts with the earlier results at Mach 3, wherein the detachment line was best characterized by a Mach number of 2.2. There remains, then, the significant problem of properly characterizing the effective detachment Mach number (if there is one) before the cylindrical/conical flow regime boundary can be considered as reasonably defined and understood.

6) Conical Similarity and its Potential as an Overall Scaling Scheme for Dimensionless 3D Interactions

As part of our work in the previous contract year, both swept and unswept leading-edge fins were experimentally investigated at Mach 3. At the end of that reporting period we had found the resulting interactions to be approximately conical in all cases, regardless of sweepback variations in the fin shock generator geometry. Further analysis of this data set revealed a potentially powerful simplification: not only is the conical nature of the interaction invariant to sweepback, but also the detailed character of the interaction was found to be dependent only upon the invisid shock angle impinging on the turbulent boundary layer. Thus an unswept fin at moderate angle of attack produced an interaction similar to a swept fin at a higher angle of attack, so long as the inviscid shock angles (β_o) for the two cases are equal.

A thorough discussion of conical similarity for swept and unswept fins has been given by Lu and Settles in AIAA Paper 83-1756. The key figure from that paper is reproduced here as Fig. 17. This figure shows that the important conical surface feature angles of fin interactions (upstream influence β_u, primary separation β_{S1}, secondary separation β_{S2}, and attachment β_A) are unique functions of the incident shock angle β_o, irrespective of a wide variation in the fin geometry. If conical

similarity was found to hold for other shock generators as well, then the cornerstone of an overall 3D interaction scaling scheme (the primary goal of the present AFOSR contract) would be established.

A comparison between the two major classes of conical interactions which we have studied extensively, fins and swept compression corners, seemed a logical step in the extension of conical similarity to a wider class of flows. This was not straightforward, however, since the impinging shock angles for arbitrary swept corners are not know a priori and are not simply calculable. An extensive set of preliminary experiments consisting of flowfield shadowgrams was required to establish a correlation of swept corner shock angle vs. the corner defining angles. At the same time we extended the conical similarity data base by running a limited set of interaction experiments with a new shock generatory geometry, the semicone, because the angles of cone-generated shock waves are known a priori from the classical Taylor-Maccoll theory.

An initial test of conical similarity for fin, semicone, and swept corner shock genrators is illustrated in Fig. 18 by comparing interaction upstream influence angles β_u on the basis of the incident shock angle β_o. This figure reveals that the results for the different geometries are generally close, lending further support to the conical similarity hypothesis. The semicone and $\lambda = 70°$ corner results are quite close, while

the fin data appear to describe a slightly different slope in β_u , β_o space.

Note that the λ = 60° corner data approach conical similarity asymptotically, since for low values of α (and thus of σ and β_o) this shock generatory geometry lies near the conical/cylindrical boundary described previously. It seems that swept corner interactions must be far from shock detachment in order to display conical similarity, which then appears to hold only at very high sweepback angles. Note also that sufficiently high values of swept corner angles α and λ tend to distort the swept corner into correspondence with the fin geometry. This demonstrates, intuitively, that there must be limits beyond which conical similarity will hold for both shock generators.

c. Progress during 1983-84

1) Study of the Conical Similarity Principle of 3-D Shock Wave/Turbulent Boundary Layer Interactions

The previous research had indicated a possible conical similarity principle. Such a principle could unite, in a common framework, the features and behavior of 3D interactions produced by geometrically dissimilar shock generators (fins, swept corners, etc.). The initial indication of such a similarity principle was at hand, though it was already known from previous work (Lu & Settles, AIAA Paper 83-1756) that conical similarity holds among interactions produced by fins of dissimilar geometry.

An extensive effort to develop this concept of a conical interaction similarity principle and to test it against the observed data was undertaken. This effort required a new series of experiments as well as an extended analysis of the problem. The results thus far have shown the basis of a similarity principle for fin and swept compression corner interactions, but the cone results have not been satisfactorily correlated. In the following sections some of the details of this study are discussed.

The 3D interaction problem is believed to depend upon stream Mach number, shock generator geometry, and the characteristics of the incoming turbulent boundary layer. In order to limit the scope of the problem, in our studies the Mach number has been held constant at a value of 2.95 and the boundary layer Reynolds number has been fixed at a value high enought to insure mean profile equilibrium.

Four generic conical shock generators have been chosen as representative cases for the present study: sharp swept and unswept fins, swept compression corners (at sweep angles > 20°), and semicones, Fig. 1. These are the "building blocks" of which such practical aircraft components as control surfaces, stabilizers, inlet ducts, canopies, etc. are comprised. While the semicone geometry is specified by a single angle, α , the other geometries require both a deflection angle, α , and a sweepback angle, λ , to specify them. Note further that, given

a sufficient range of α and λ , the fin and swept corner geometries seem to belong to the same family.

A knowledge of the position of the inviscid shock trace in the plane of the boundary layer is required as a basis for the coordinate frame. However, determining β_o is not trivial. It is known a priori only for unswept fins (from the exact oblique shock theory) and for semi-cones (from Taylor-MacColl theory). For swept fins and compression corners, no simple soluions exist, and the theoretical determination of the shock shape requires a shock-fitting computational Euler solver. Not having such a code at hand, we have instead measured a wide range of shock shapes directly from shadowgrams of the flow over rhombic cones and delta wings at angle of attack. The latter results were correlated and reported by Lu & Settles.

For later use it is important to know not only the inviscid shock angle β_o, but also the shape of the shock in the vicinity of the swept corner. Prior to detachment the shock is, of course, planar. Beyond detachment we can make a first approximation that the shock follows some circular arc in the corner vicinity, by analogy with previous studies of 2D detachment from wedges. By taking shadowgrams of several rhombic cone models at various roll angles, it was possible to plot the corresponding shock shapes and thus obtain several r/x vs. σ_0 (the detachment angle) data points. M.D. Salas has also computed and published

the shock shapes for five swept corner cases at Mach 3 in AIAA Paper 79-1511.

Given the above background, we searched for an appropriate form for a similarity principle to possibly unite the disparate characteristics of fin, semicone and swept corner interactions. In the simplest case, a single "interaction response function" would express, in a global sense, the interaction characteristics. While it is not obvious that such a function exists, experience has shown us that a measure of the interaction upstream influence (necessarily an angular measure β_u in a conical flow) serves this purpose admirably. However, the use of upstream influence alone has been criticized on the grounds that it fails to indicate the downstream effects of the interaction. Therefore, as an improved response function, we propose to use the included conical angle $\beta_{S1} - \beta_{A1}$ between the two most obvious features of the interaction footprint: the sharp "convergence line" shown by most of the oil flow studies and designated as the "separation", and the area of divergent surface flow line, designated as the "attachment." It should be noted that this definition is <u>not</u> applicable for all cases, i.e. at low deflection angles of the fin and wedge, no such characteristics are observed.

As shown schematically in Fig. 19 for a swept corner interaction, this parameter expresses the nondimensional lateral spreading rate of the interaction. In principle, the lines S1

and Al are topological features of the interaction footprint corresponding to loci of confluence and divergence, respectively, of the surface skin friction lines. For the present interactions, we have observed possible boundary layer separation at Sl and attachment at Al by way of flow visualization techniques cf. Settles & Teng, AIAA Journal, March 1983) but there is still some question of the interpretation of these results. We are cautious, however, not to assume that such surface lines always correspond to separation and attachment in any given flows and note again that these features are not always observed in all flows.

An extensive set of experiments and analyses were carried out to study the concept of interaction response function. In the connection of the response function to the observations of surface oil flows, it was found that the interaction characteristics depended primarily on the inviscid shock wave strength and shape. When characterized by an overall angular "interaction response function," the flow studied here can be correlated by a simple linear dependence on inviscid shock angle and radius of curvature. It appeared to be that the position of the reattachment line, whether on the shock generator or the test surface, was a critical issue since there appears to be an apparent change in the normal Mach number influence on interaction size. A conical "free interaction" principle, similar to that for 2D flows, was derived. Given similar values of shock and

upstream influence angles, the footprint topology of fin, semi-cones, and swept corner interactions was found to be virtually identical (Fig. 20). Surface pressure similarity was also demonstrated (Fig. 21). These results form the basis of a general conical similarity scheme which unites the features of several geometrically dissimilar shock generator families. There are, however, clearly some key unanswered questions although the general concept noted above seems to be applicable for a relatively wide range. One of the most striking features is what appears to be the global connection between swept corners and fin interactions, but the lack of correlation with the cone results at this time. We have also no clear physical understanding of the phenomena although we have been quite successful in our scaling attempts.

2) High Angle of Attack Sharp Fin Studies

With the major study of swept wedges completed and providing the base for extensive analyses, it became clear that the original sharp fin studies generated shock strengths which were not as strong as those for the wedge studies. Since the sharp fin interaction, we believe, is a simpler interaction, and the shock strength is an important parameter in our scaling, we initiated a study to extend the sharp fin to much stronger shock strengths. Physical limitations on the ability to "start" the tunnel with high angle sharp fins of fixed geometry required the construction of a new model of variable geometry, Fig. 22. This

geometry provided the ability to start the tunnel at low angles (fin angles of approximately 12°). Once the tunnel flow was established, the wedge angle could be increased until choking of the tunnel took place. Results were obtained for angles of the fin as high as 22°. The results of these studies were detailed in the Master's degree of Scott P. Goodwin. Both surface pressure data and surface flow visualization results were obtained. The following conclusions could be drawn:

(1) The surface flow features of strong shock-induced interactions, with the exception of secondary separation, are qualitatively similar to those observed at lower angles of attack. The upstream extent of the interaction was seen to simply increase with increasing shock strength.

(2) Using both surface flow visualization and surface pressure data, sharp fins have been demonstrated to produce approximately conical surface feature for angles of attack up to 22°.

(3) The upstream influence scalig scheme of Dolling and Bogdonoff was shown to be valid for sharp fins at angles of up to 22° at a Mach number of 2.95, thus increasing the generality of the principle.

(4) The present data, as well as that of Oskam, showed that the streamwise upstream influence length was proportional to the freestream Mach number.

In addition to the general conclusions a series of important observations were made of importance in our general overall scaling. As the angle of attack of the fin was increased the location of the virtual origin of the conical flow moved closer to the fin leading edge in both the streamwise and spanwise direction. The line of convergence, "separation," was found to occur at a pressure level of approximately 85% of the plateau pressure determined from the wall static pressure distributions. This "separation" pressure ratio increased with increasing angle of attack, increasing unit Reynolds number, and decreasing boundary layer thickness. A feature called "secondary separation," which developed and then disappeared during the variation of fin angle from 12° to 22°, was also found to depend on boundary layer thickness as well as on shock strength. It appeared to be associated with the dip in the streamwise pressure distribution which was dependent on the boundary layer thickness. Since this data set was the first for this configuration at high shock strengths, direct comparison with the computations of Knight and Horstman were of particular importance. Both the computations of Knight at an angle of attack of 20°, Fig. 23, and those of Horstman at 16° showed only fair agreement and has been the basis for continued refinement of the computational methods. Strong differences and similarities with two-dimensional interactions were observed. The three-dimensional data were quite different in that the initial pressure rise changed as the shock

strength increased, getting stronger as the shock strength increased. In two dimensions, the initial part of the pressure distribution remained constant once the flow separated, and the gradients were less than the weaker shock cases where the flow was not separated. The Reynolds number dependence for both two- and three-dimensional interactions were markedly similar.

3) Review of Different Data Sets

Although reviewing the present and past work was a continuing part of the subject contract, during this period special emphasis was placed on trying to re-examine a series of questions which had arisen as the research had progressed. These questions were primarily concerned with surface features, flow field visualization, the conical/cylindrical boundary, and the question of steadiness. We continued to search for techniques which would connect the surface features with the surface pressure distributions and the flowfield surveys that have been made. Many comparisons were made of pressure distributions and surface flow visualization. An example is Fig. 24. The upstream influence line from surface flow visualization always seems to agree with the first indication of the pressure rise from the wall static pressure distribution. This also agrees with the first flowfield disturbances that are determine from flowfield surveys. The line of surface flow convergence, usually designated as "separation," was found by Goodwin to be at approximately 85% of the plateau pressure. This pressure ratio depended weakly on the test

variables but increased with increasing shock strength. The pressure ratio decreased as the boundary layer thickness increased. The pressure ratio also increased as the unit Reynolds number was increased. With increasing shock strength, this feature tended to occur further upstream of the inviscid shock location. We have not, thus far, been able to connect any of the flowfield surveys with this feature on the wall, although some considerable effort has been spent in trying to do so.

The variable angle studies of Goodwin gave the opportunity to examine the feature called "secondary separation". Secondary separation seemed to coincide with the initial peak of the streamwise pressure distribution although many times it was located past the peak. As with other features of the surface flow, it moved closer to the shock as the unit Reynolds number was increased, agreeing with other results available in the literature. There was, however, a significant effect which appeared to depend on the thickness of the incoming boundary layer. All of the features noted above were clear when the boundary layer was thin. When the results were compared to a thick boundary layer (factor of 4 thicker) the surface feature was no longer visible and the pressure distribution was also modified so that there was less of a dip after the initial peak. Again, there were no features of the flowfield survey which appeared to be connected with this observation.

Local vapor screen has thus far provided one of the few methods of flow visualization which have been applicable to the complex interactions under study. It was found, however, that the interpretation of the data obtained was difficult because of the highly three-dimensional nature of the interaction which had to be inferred from two-dimensional observations (light sheets). Although the light screens seem to show flows that lift from the surface, it should be noted that this impression cannot be validated in practice because no illuminated particle at one part of the observation came from the initial part of the interaction as observed from the light screen. Each particle observed comes by a different path from a different location in the upstream flow. These initial conditions are unknown. Considerable further work is required to interpret these results, and what is needed is a method for tracing streamlines rather than illuminating particles in arbitrary two-dimensional planes.

The conical/cylindrical boundary for swept wedge flows was established by Teng & Settles, Fig. 2. The major conical similarity work has been restricted to the upper right-hand area. It should be noted that conical flows in the region designated is an observation of the general characteristics. To try to use the results in engineering calculations, one must know the location of the virtual origin of the conical flow, and this is not known a priori. As one approaches the suggested boundary, the virtual origin moves further and further from the physical apex of the

model (it obviously is at infinity when the so-called border is crossed and the flow becomes cylindrical). Such a boundary was also established for Mach 2. There still is some considerable question as to the physics involved in the boundary and, in particular, how the boundary at variable Mach numbers might be estimated. At the same time, our studies have been able to establish that the boundary for the full flowfield is not as sharply defined as suggested in the original test series.

The question of steadiness has become more and more important as high frequency instrumentation has been applied to turbulent shock wave boundary layer interactions. A study of the unsteadiness of the separation shock structure on a two-dimensional compression ramp, by Dolling & Murphy, showed how far from mean conditions this flow actually was during a large fraction of the time. This work, and the work on the blunt fin, have posed a serious question which until now has been unanswered for three-dimensional interactions. The specific application and understanding of much of our modeling is based on the assumption that the flow is steady. The usual assumption is that, in turbulent flows the known unsteadiness does not significantly affect the mean values obtained from experiment or computation. Questions of the effect of unsteadiness on turbulence modeling is a completely unexplored area. These considerations dictated

initiation of the new program noted in one of the following sections.

4) Interactions with Computational Groups

The interactions with Dr. C. C. Horstman of NASA-Ames and Prof. Doyle Knight of Rutgers were increased during the subject period as closer and closer collaboration has been developed. As noted earlier, the first results from stronger shocks generated by sharp fins stimulated a new set of computations. In general, the computations have always seemed to be approximately correct for the upstream influence line. They do not seem to be able to predict a secondary separation line. For increased shock strengths, which exhibit sharp changes in the pressure distribution, (as exhibited by higher swept wedges and strong sharp fin shocks) the computations generally reflect the overall pressure distributions but much of the detail is missed. Many of the stronger gradients are usually underestimated. Continued interplay between the computations and the experiments are clearly important. From the experimental point of view, if validated computations can be obtained, the computations provide a way to do studies of the flowfield which are thus far not possible from experiment. From the computational point of view, the major contribution is to determine where the arbitrary turbulence models and computational models used give reasonable results.

5) <u>High Frequency Studies</u>

The first studies of surface pressure fluctuations in a three-dimensional shock wave turbulent boundary layer interaction were carried out by Tan, et.al. on the 10° sharp fin, the original configuration studied by Oskam and examined in considerable detail by McClure. A set of four high frequency gauges located 0.2" apart, were aligned with the flow direction and also parallel to the upstream influence line in separate tests. Pressure fluctuations were found to be small, in contrast to the very large disturbances found in a two-dimensional compression ramp shock wave boundary layer interaction with the same shock strength. Cross correlation analyses suggests some degree of unsteadiness in the shock structure. This initial study has shown that appropriate measurements can be made using these new techniques and clearly extension to variable shock angle is required. The data of Fig. 25 and 26 show that the high frequency gauges, when time-averaged, give about the same results as the standard static pressure orifices. It also shows that there are significant changes in the fluctuation levels through the interaction. The details and structure of these fluctuations are not understood, but seem to follow the trend shown in other work which indicates that pressure increases amplify the disturbances in the original turbulent boundary layer. The effect of the three-dimensional structure and of the "separation" (if it is present) has yet to be examined.

IV. CONCLUDING REMARKS

The subject contract has supported an extensive experimental study of three-dimensional shock wave turbulent boundary layer interactions caused by shock generators defined solely by angles. These geometries, sharp fins, sharp swept fins, and swept wedges, the original group studied, was supplemented by a few tests of semi-cones during the latter part of the program. Surface flow visualization results were obtained for all geometries, many surface static pressure distributions were obtained, and two detailed flowfield surveys of total head and yaw were carried out. Numerous attempts were made to visualize the flowfield and some exploratory studies using high frequency surface pressure gauges were carried out to evaluate the steadiness of the flows. The technical results have been presented in detail in 21 reports and publications and 7 presentations at national meetings.

Four major data sets were developed. The 10° sharp fin and the 24-40° swept compression corner were used for full flowfield surveys of total pressure and yaw angles. Sharp fin studies from 12° to 22° were carried out by examining surface pressure distribution and flow visualization. An extensive matrix of surface flow visualization of wedge angles up to 24° and sweep angles up to 70° has been carried out. These tests have provided extensive new information on three-dimensional shock wave

boundary layer interactions and provided a broad base to check calculations.

Significant contributions were made in each area of "proposed tasks" of the original proposal. Extension of the original scaling laws were derived, and a major contribution was made in showing a flowfield similarity for the initial part of the interactions of the same strength shock generated by different shock generator geometries.

The major extension in the available data base has given indications of possible physical mechanisms and flow structures. However, available instrumentation has not been adequate to clearly define the details of the structure nor reveal the complex physical mechanisms which are involved in this flowfield. Several possible mechanisms have been proposed, each supported to some degree by some of the results, but the available experiments are not conclusive. The classification of flows as conical or cylindrical, the concept of "separation," and the steadiness of the flow have all been described in general terms. The conical/cylindrical boundary is not as sharply defined as originally conceived, separation, as indicated by surface flow visualization, has not been found to significantly influence the flowfield and, although the flows have been found to be unsteady, the unsteadiness is considerably less than that of two-dimensional separated flows.

V. LIST OF PROFESIONAL PERSONNEL INVOLVED IN THE CONTRACT EFFORT

Andreopoulos, Yiannis, Research Staff Member and Lecturer, Mechanical and Aerospace Engineering Department, Gas Dynamics Laboratory. (Arrived May 1984.)

Bogdonoff, Seymour M., Professor, Mechanical and Aerospace Engineering Department: Director, Gas Dynamics Laboratory.

Dolling, David S., Research Staff Member and Lecturer, Mechanical and Aerospace Engineering Department, Gas Dynamics Laboratory. (Left July 22, 1983, to accept position as Assistant Professor, University of Texas, Austin.)

Settles, Gary S., Research Engineer and Lecturer, Mechanical and Aerospace Engineering Department; Manager, Gas Dynamics Laboratory. (Left July 31, 1983, to accept position as Assistant Professor, Penn State.)

Smits, A. J., Associate Professor, Mechanical and Aerospace Engineering Department, Gas Dynamics Laboratory.

Tan, David K. C., Research Staff Member, Mechanical and Aerospace Engineering Department, Gas Dynamics Laboratory. (Arrived October, 1983.)

Teng, H.-Y., Research Staff Member. (Visiting Research Engineer from China - returned August 1982.)

Graduate Students

Lu, Frank K.-P., "An Experimental Study of Three-Dimensional Shock Wave Boundary Layer Interactions Generated by Sharp Fins," MSE Thesis #1584-T, December 1982.

McClure, William B., "An Experimental Study into the Scaling of an Unswept-Sharp-Fin-Generated Shock/Turbulent Boundary Layer Interaction," MSE Thesis #1597-T, January 1983.

Murphy, Mark T., "An Experimental Investigation of the Separation Shock Wave Unsteadiness in a Compression Ramp Flowfield," MSE Thesis #1605-T, May 1983.

McKenzie, T. Michael, "A Flow Field Scaling of the Three-Dimensional Shock/Boundary Layer Interaction of the Swept Compression Corner," MSE Thesis #1598-T, June 1983.

Kimmel, R., "Conical Similarity in Shock Wave Boundary Layer Interaction," Ph.D. Thesis in preparation.

Tran, T., "Experimental Studies of Mach Number Effects in Shock Wave/Turbulent Boundary Layer Interactions," Ph.D. Thesis in preparation.

VI. SCIENTIFIC INTERACTIONS

During the 3-year period of the subject contract, staff and students carrying out the research program interacted strongly with many organizations and individuals outside of the Gas Dynamics Laboratory. The research program was a focus for a significant group involved in studies or applications of shock wave turbulent boundary layer interactions. Many discussions were very helpful in the formulation of plans for the experiments, interpretation of results, and clarification of concepts.

Outside of the many usual contacts at technical meetings, visits and seminars at other research and industrial laboratories, and visits and seminars by others at the Gas Dynamics Laboratory, several very strong and important interactions developed in collaborative efforts which had a significant impact on the research program. Probably most important was the early development of links with the strong computational group at NASA-Ames, through Dr. C. C. Horstman, and later the close connection established with Prof. Doyle Knight at Rutgers. These two groups are probably the foremost researchers working on the development of computational techniques for the solutions of the Navier-Stokes equations and the application of these solutions to high-speed complex interactions. Many meetings and telephone discussions were important elements in the planning of the tests and computations, and in the review and critique of both the data sets generated and the efforts of the

computation to duplicate the results. The results of the interactions have ended up in several jointly authored papers. These papers are rather unique and very important in the development of not only understanding, but engineering techniques to use the results in practical applications. The problem of turbulence modeling in such interactions is one of the most difficult unsolved problems in fluid mechanics. The inadequacy of the present turbulence models, in some cases, or the insensitivity of the phenomena to the turbulence model in others, could only be determined by the detailed comparison of specific experiments and computation.

The interactions and collaboration with Prof. George Inger of the University of Colorado, provided an input of analytic study based on triple deck theory and attempts to model the complex flows of the interactions under consideration. The many discussions with Prof. Inger which were particularly helpful in developing physical insights of the possible underlying principles in various areas of the flowfield.

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August 4, 1981 thru July 31, 1984

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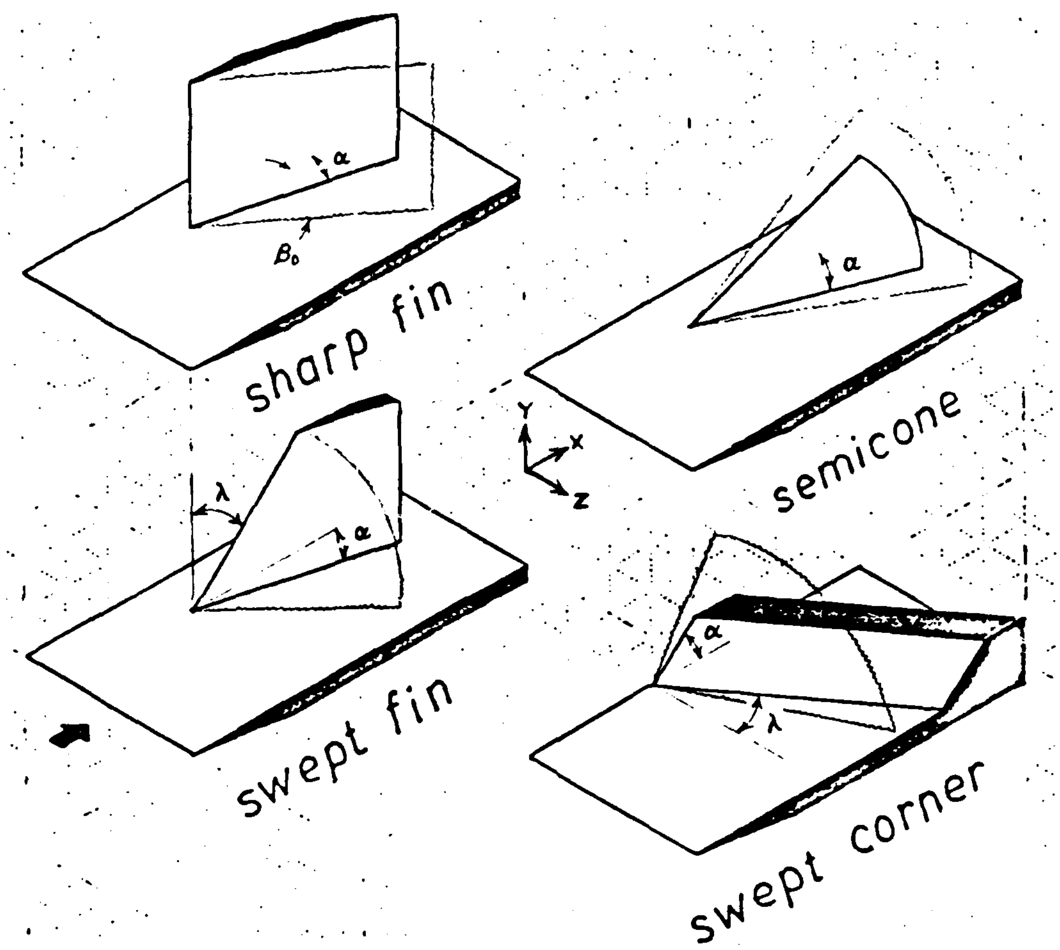

Fig. 1. Shock Generator Geometries

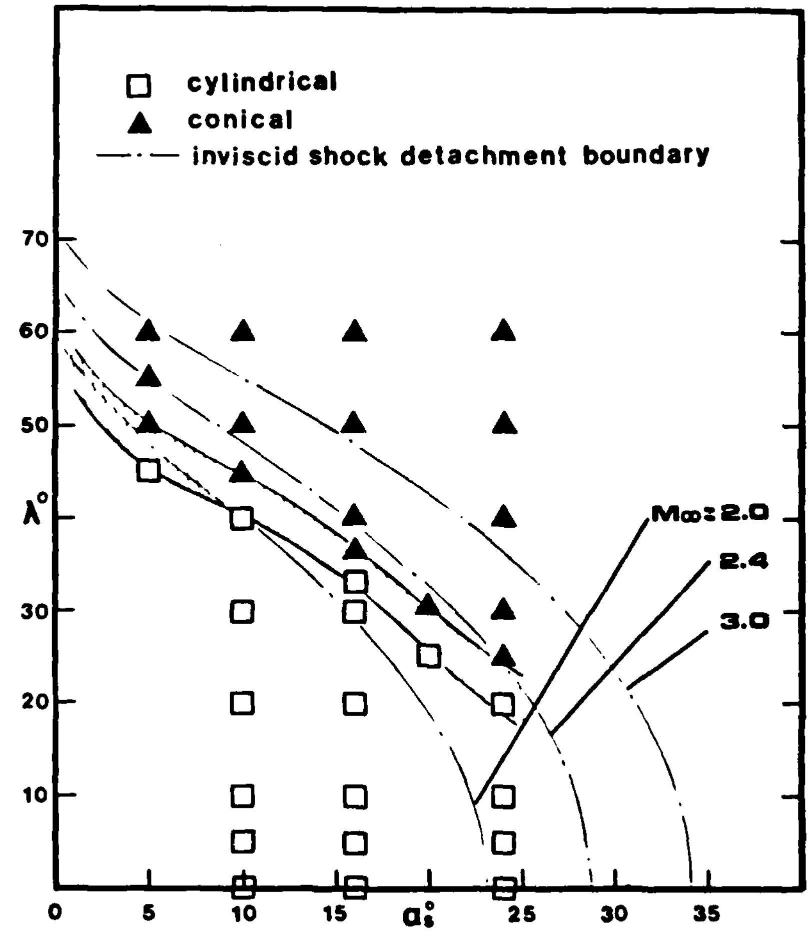

Fig. 2. Cylindrical/Conical Flow Regime Boundary for Swept Corner Interactions with $M_\infty = 3$.

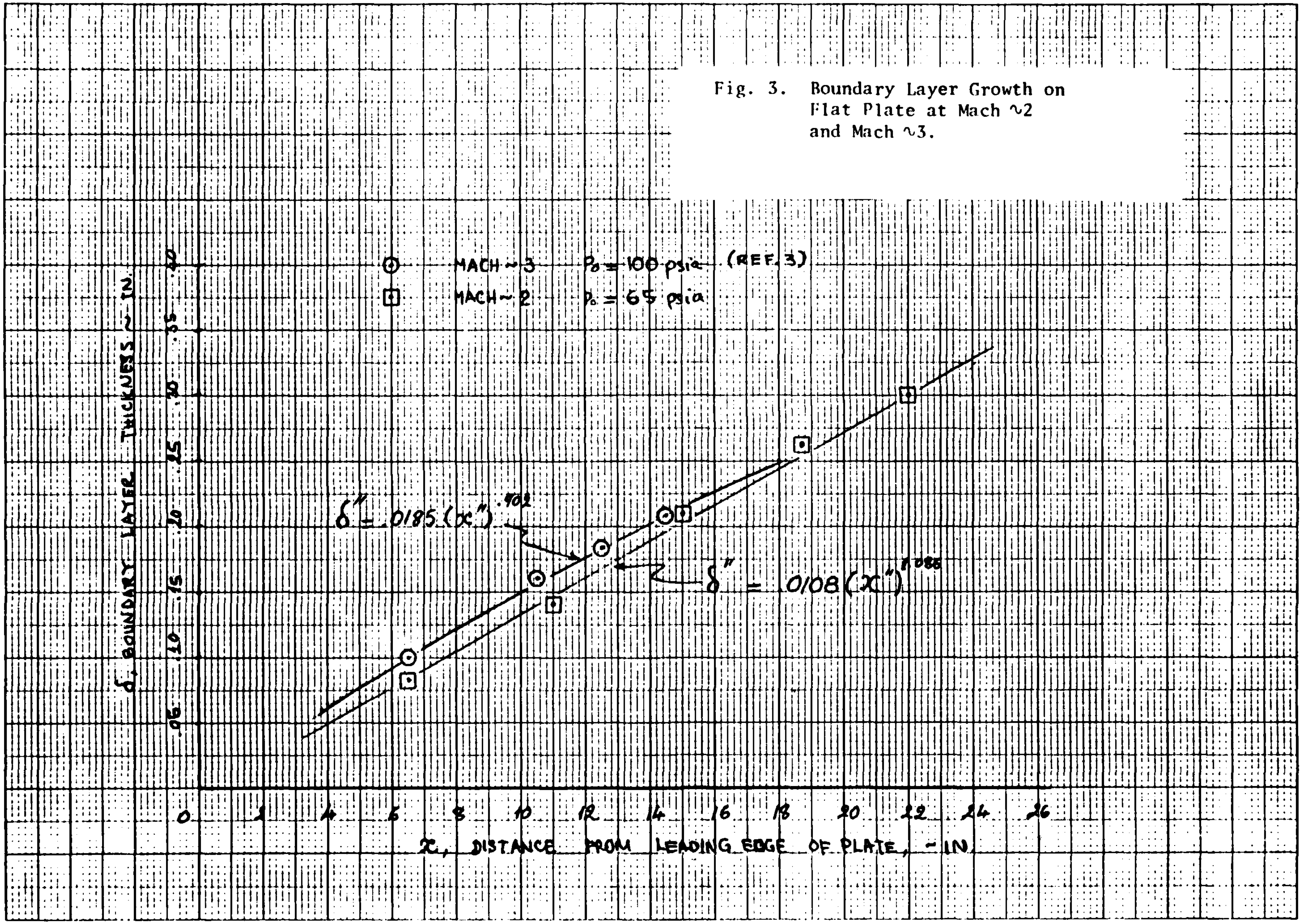

Fig. 3. Boundary Layer Growth on Flat Plate at Mach ~2 and Mach ~3.

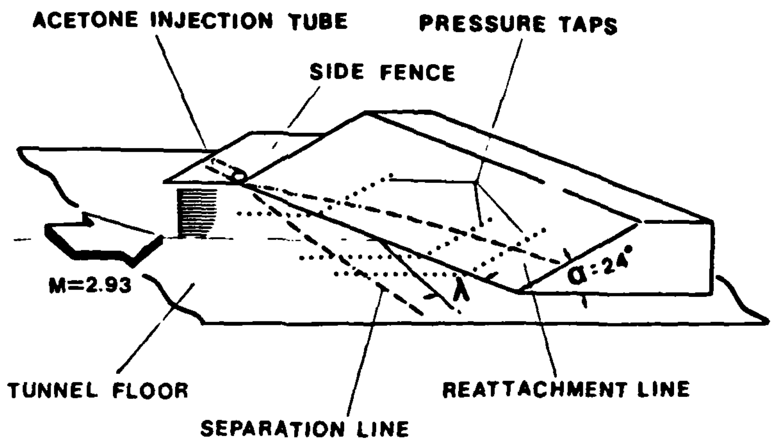

Fig. 4. Sketch of Swept Compression Corner Geometry.

Fig. 5. Stereo Pair Showing Acetone Injection Upstream of Separation Zone (λ = 40°).

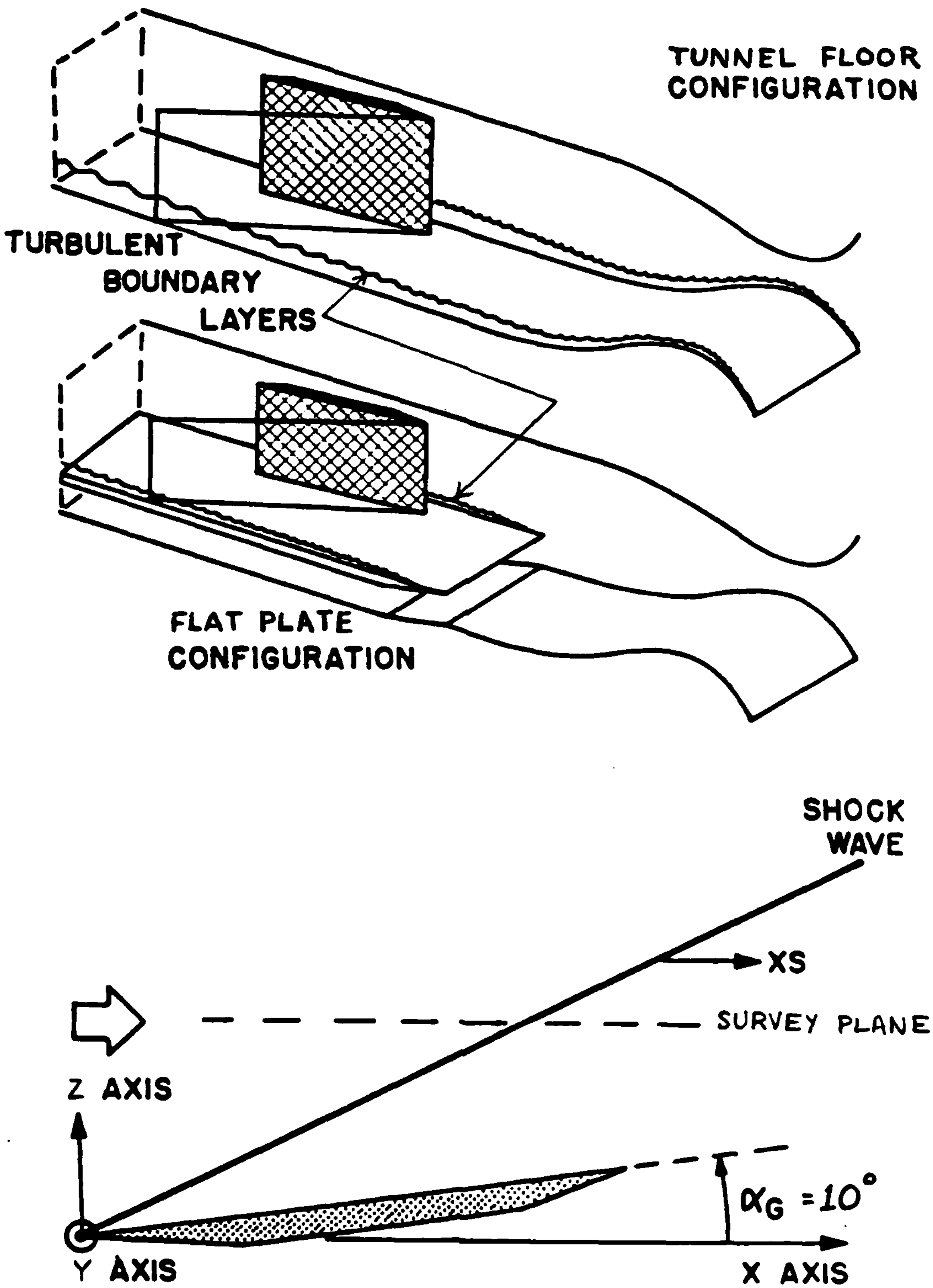

Fig. 6. Flow Configurations and Coordinates for Cobra Surveys of Swept Shock Interaction.

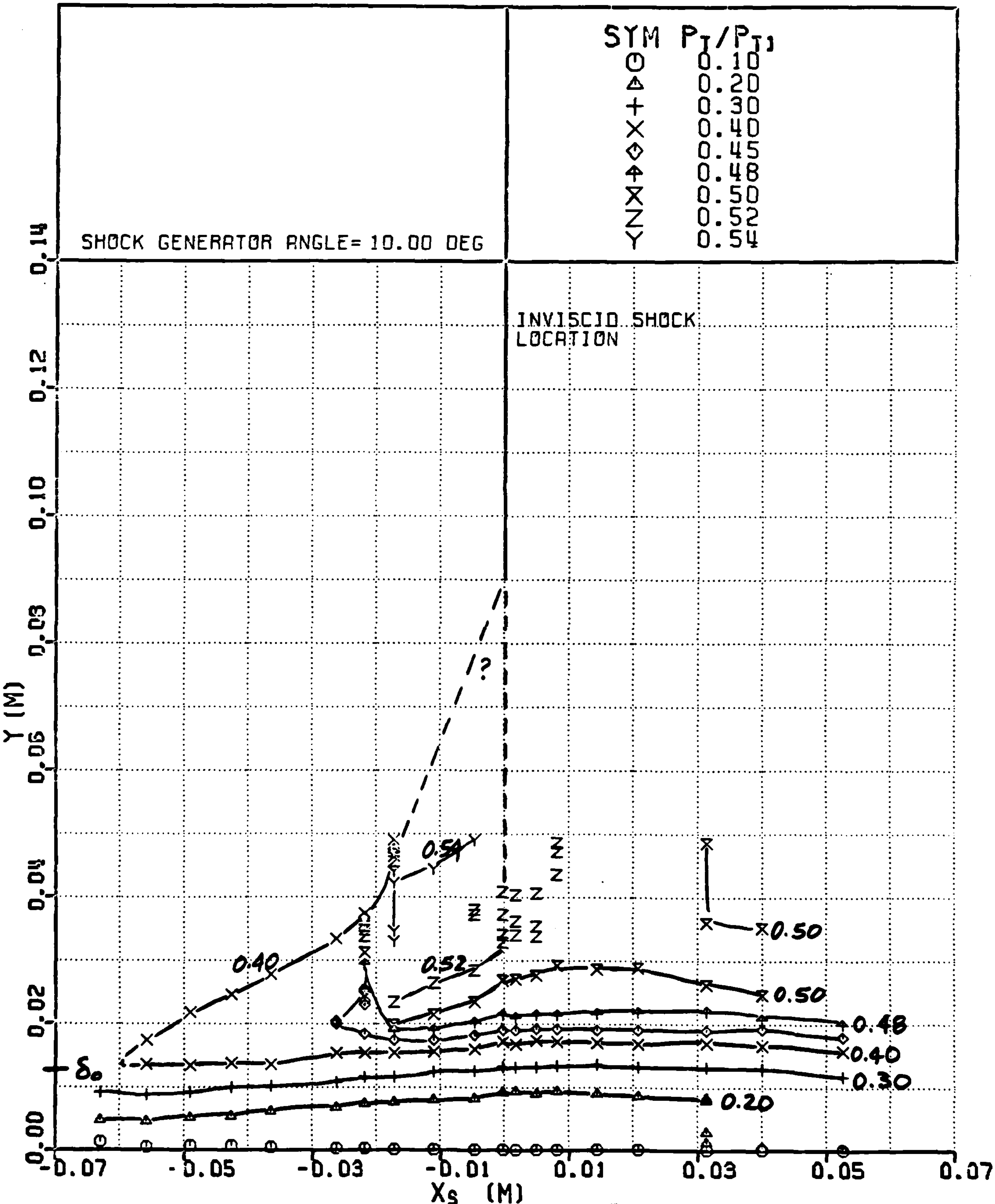

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Fig. 7. Pitot Pressure Profiles in Swept Shock Interaction (Tunnel Floor Boundary Layer).

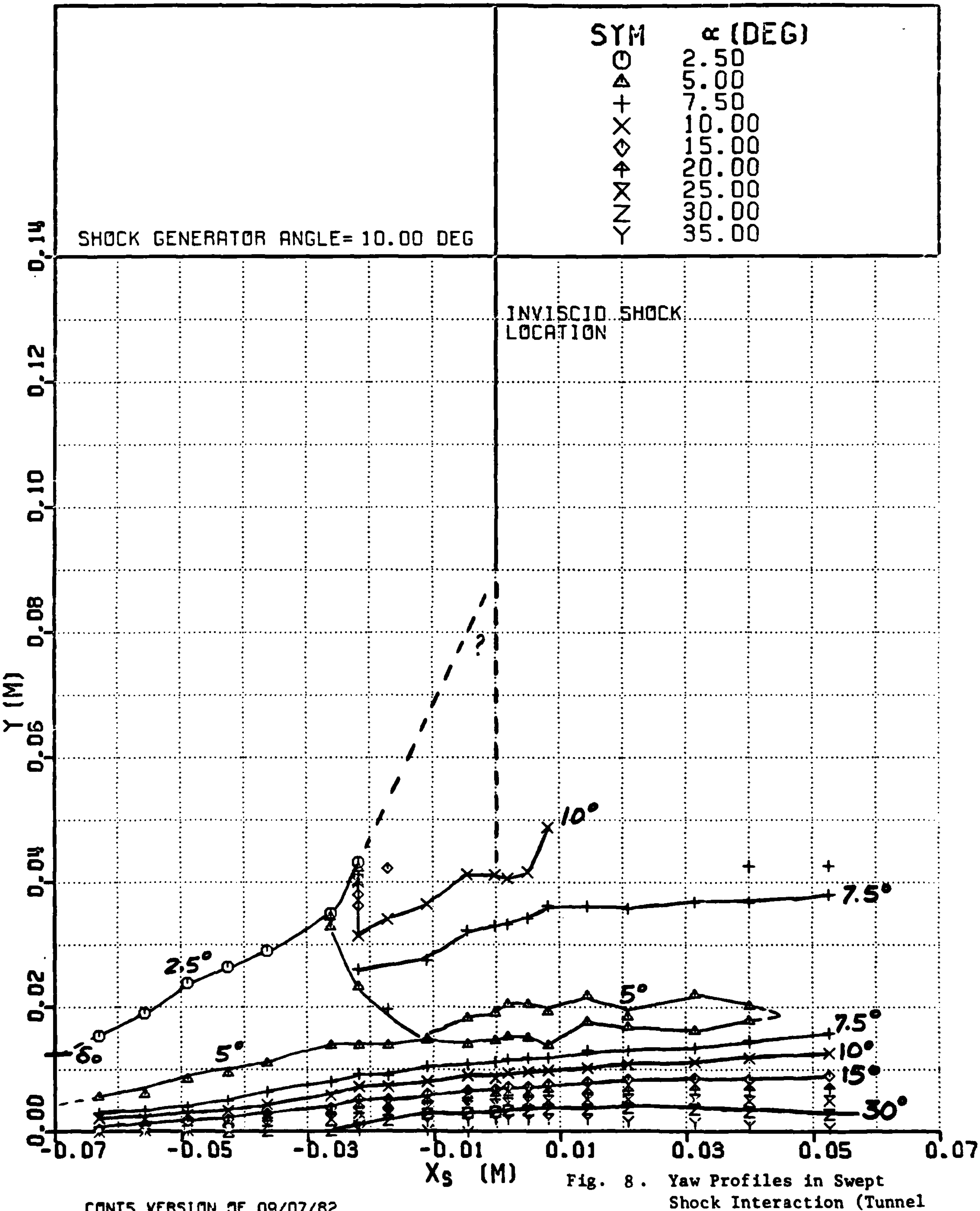


Fig. 8. Yaw Profiles in Swept Shock Interaction (Tunnel Floor Boundary Layer).

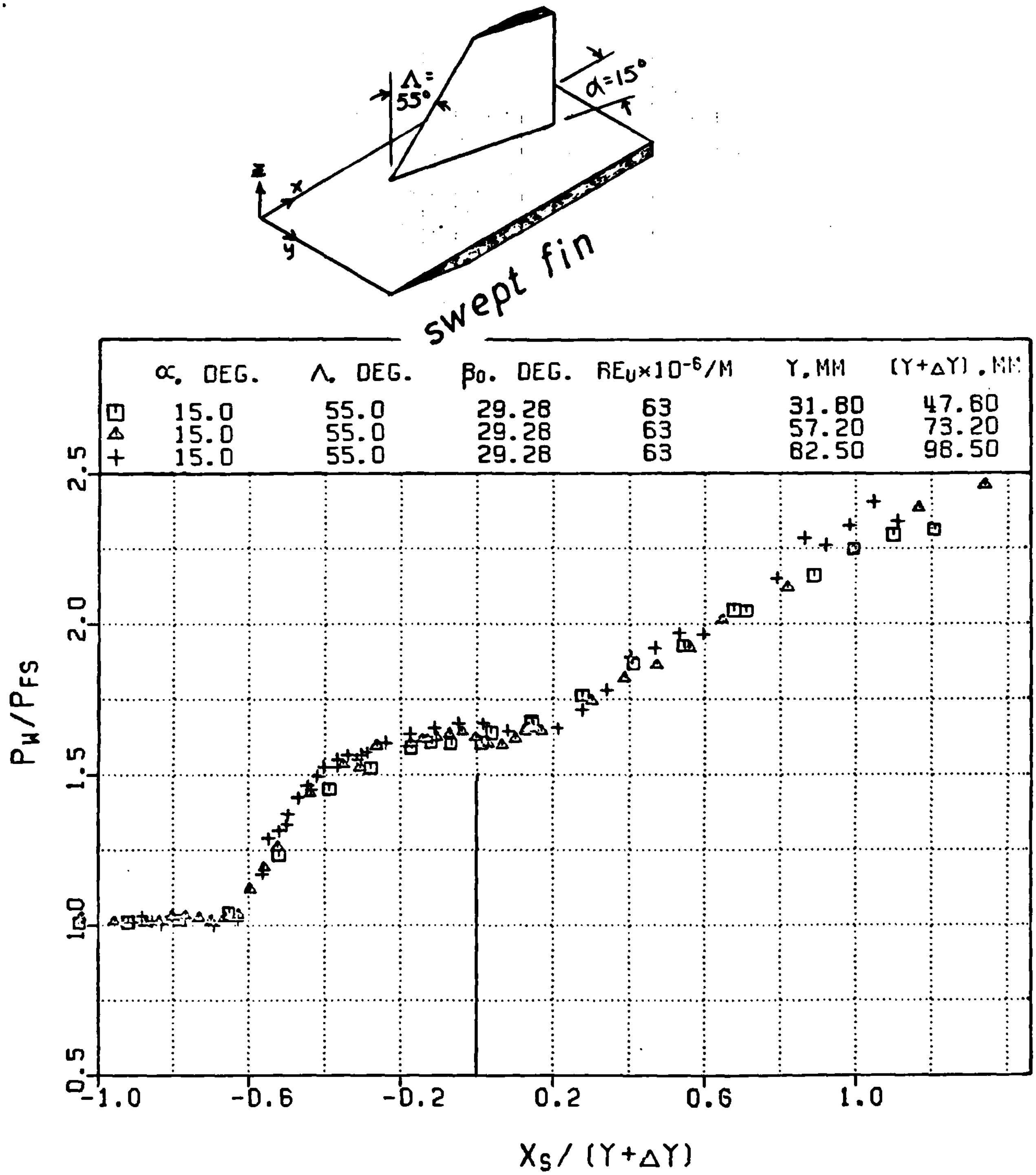
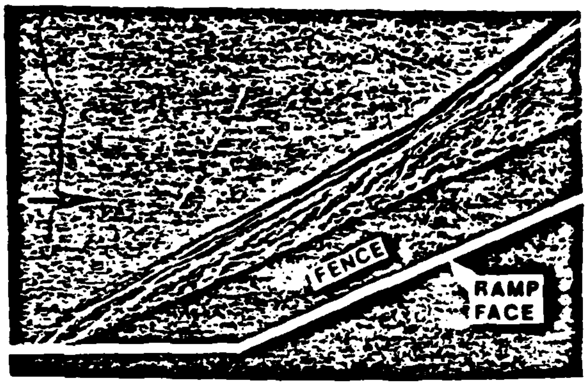


Fig. 9. Streamwise Surface Pressures from Swept Fin Experiments, Collapsed in Conical Coordinates.



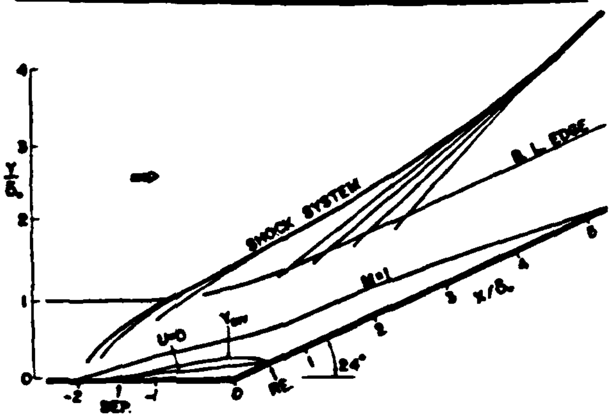


Fig.10-a) Micro-second Spark Shadowgram of Interaction, and
-b) Experimental Mean Flowfield Model (from Ref. 17)

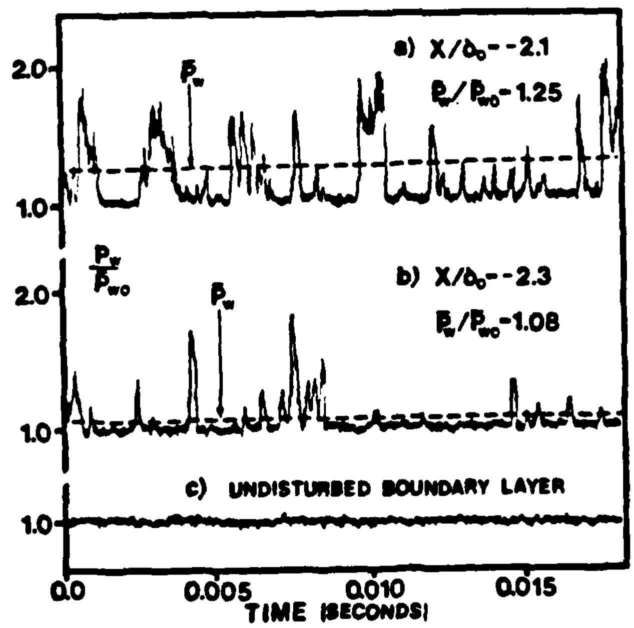


Fig.11. Pressure-Time Histories Near Separation.

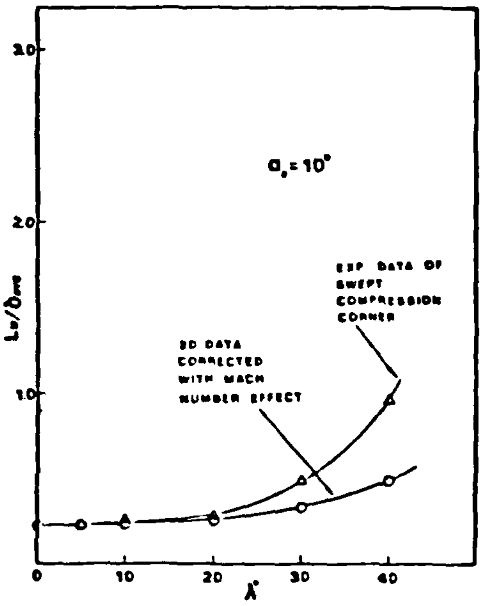


Fig. 12a. Comparison of Swept Cylindrical and 2D Data to Test Independence Principle, $\alpha_s = 10^{\circ}$.

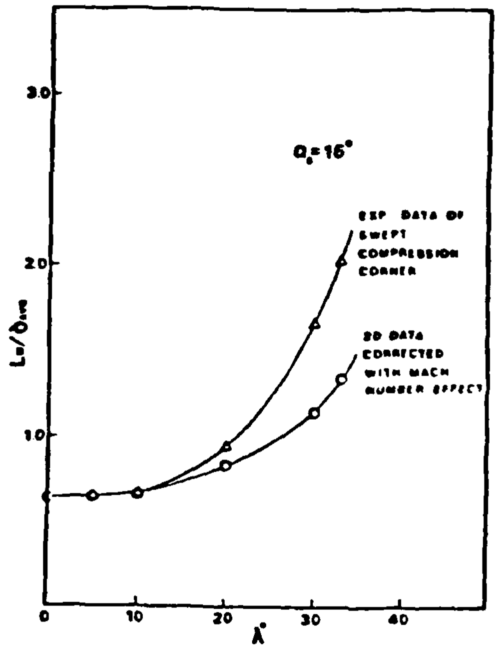


Fig. 12b. Comparison of Swept Cylindrical and 2D Data to Test Independence Principle, $\alpha_s = 16^{\circ}$.

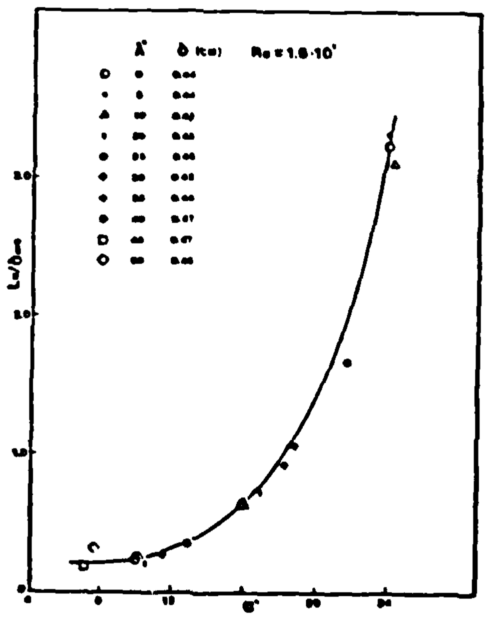


Fig. 13. Comparison of 2D and Swept Cylindrical Data Corrected for Crossflow Effect.

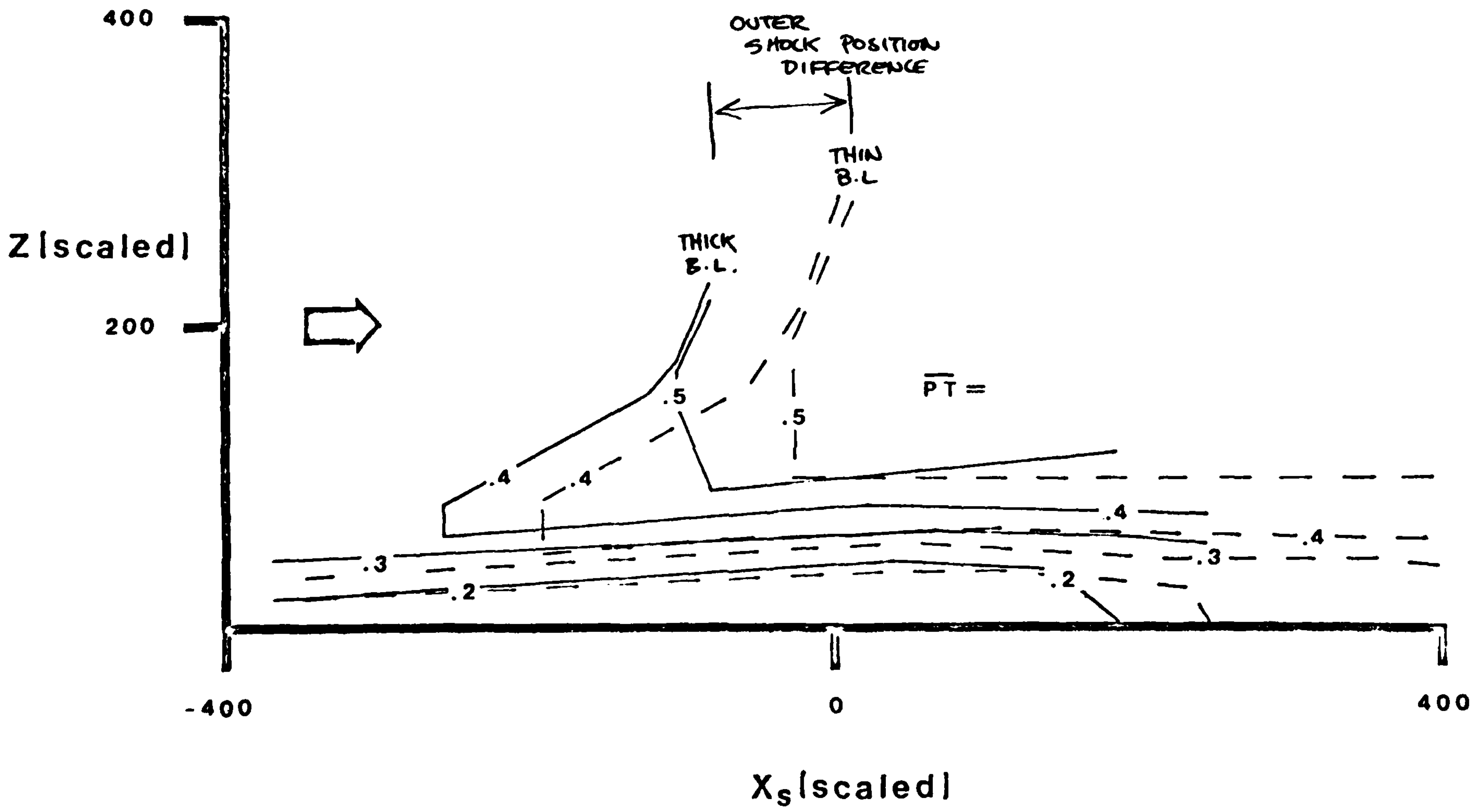


Fig.14. Pitot Pressure Contours of $\alpha = 10^{o}$ Fin Flowfield, Thin and Thick Boundary Layer, Correlated by Reynolds Number Scaling Law.

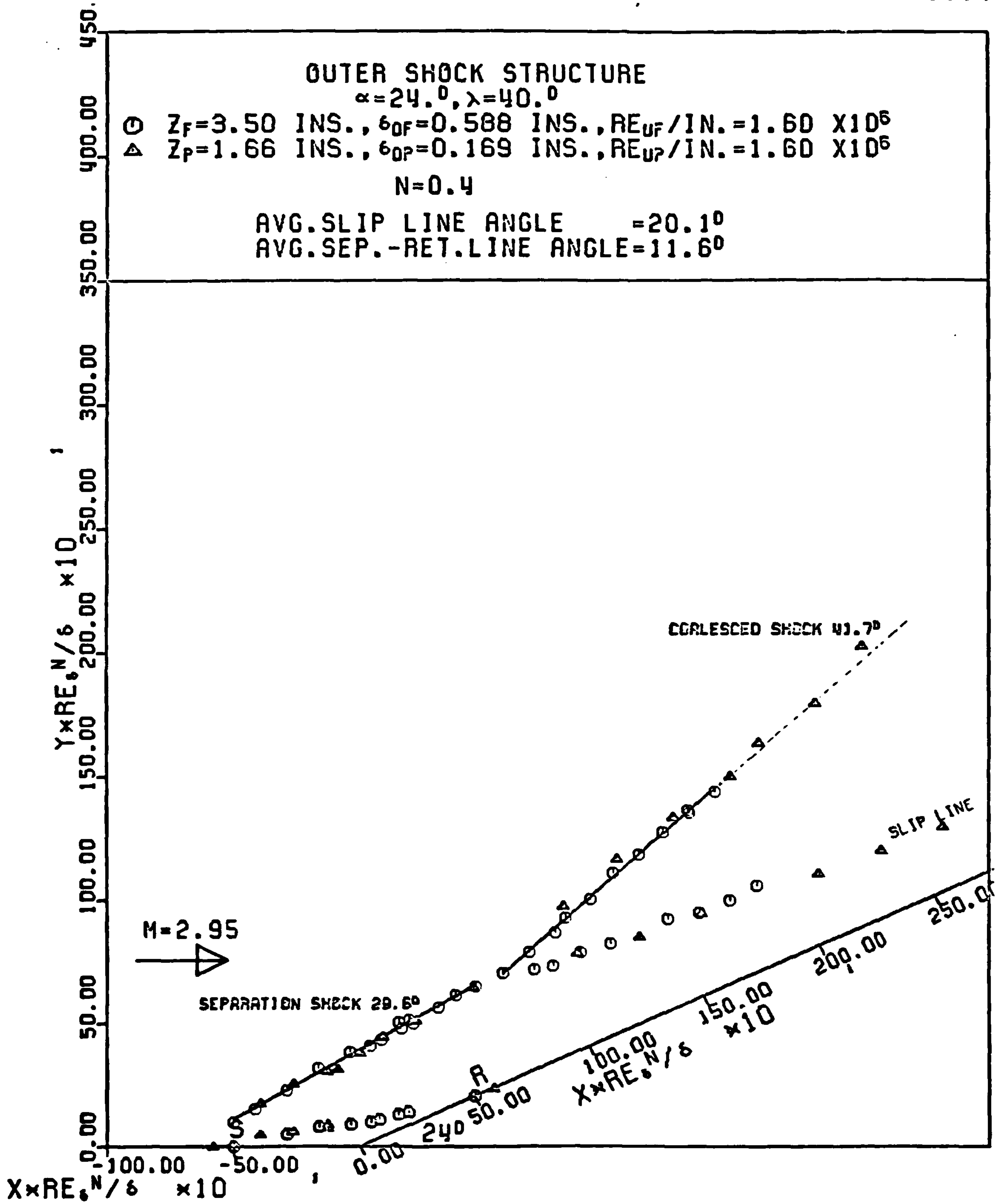


Fig. 15. Scaled Plot of Flowfield Features of 24-40 Swept Corner Interaction for Both Thin and Thick Boundary Layers.

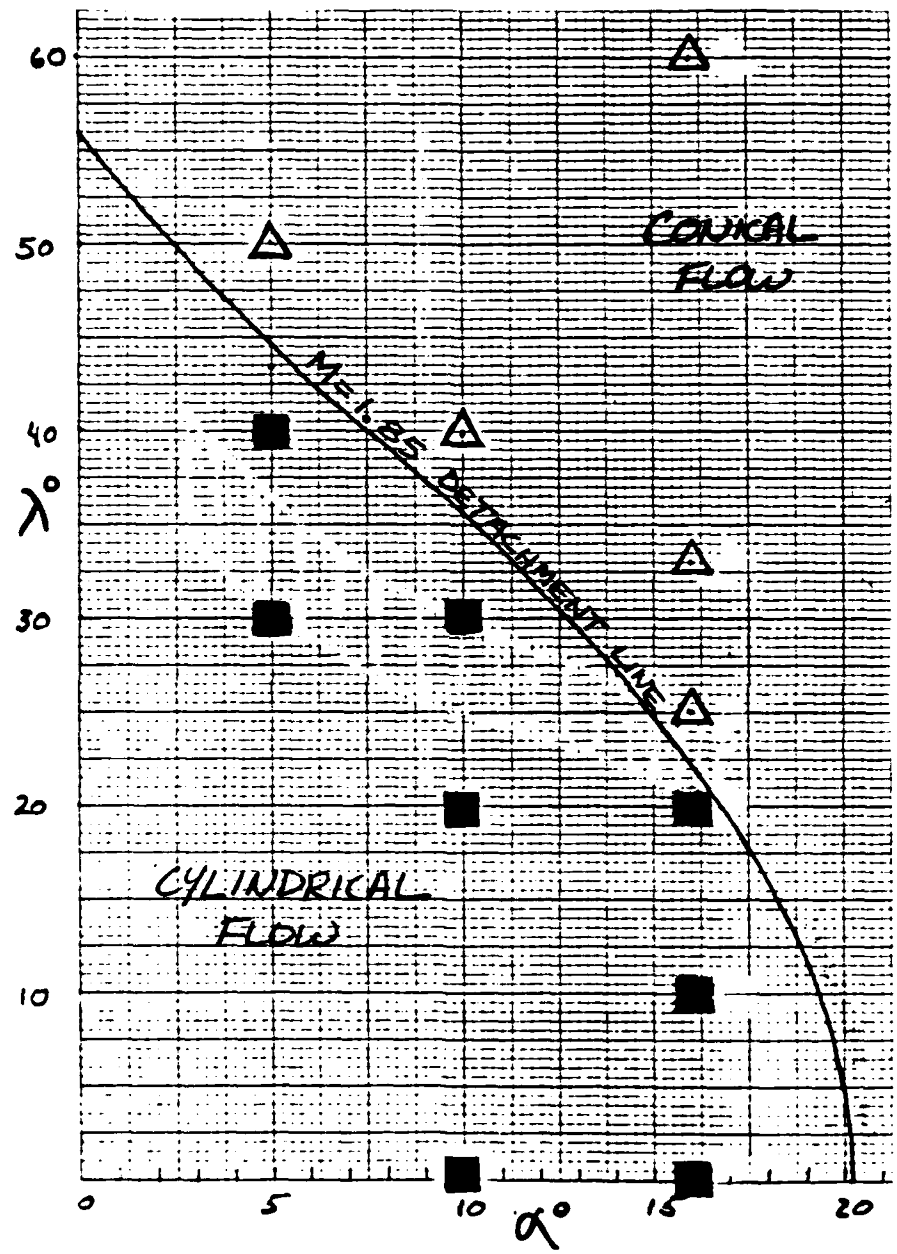


Fig. 16. Cylindrical/Conical Boundary for Swept Compression Corners at $M_\infty \sim 2$.

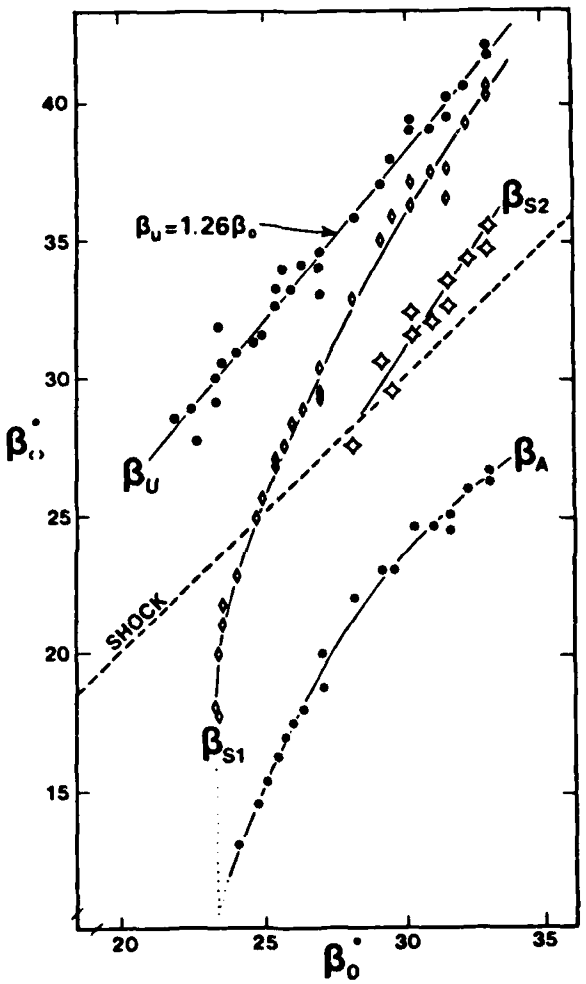


Fig. 17. Angles of Conical Interaction Features vs. Inviscid Shock Angle, Demonstrating Results of Parametric Variations of α and λ.

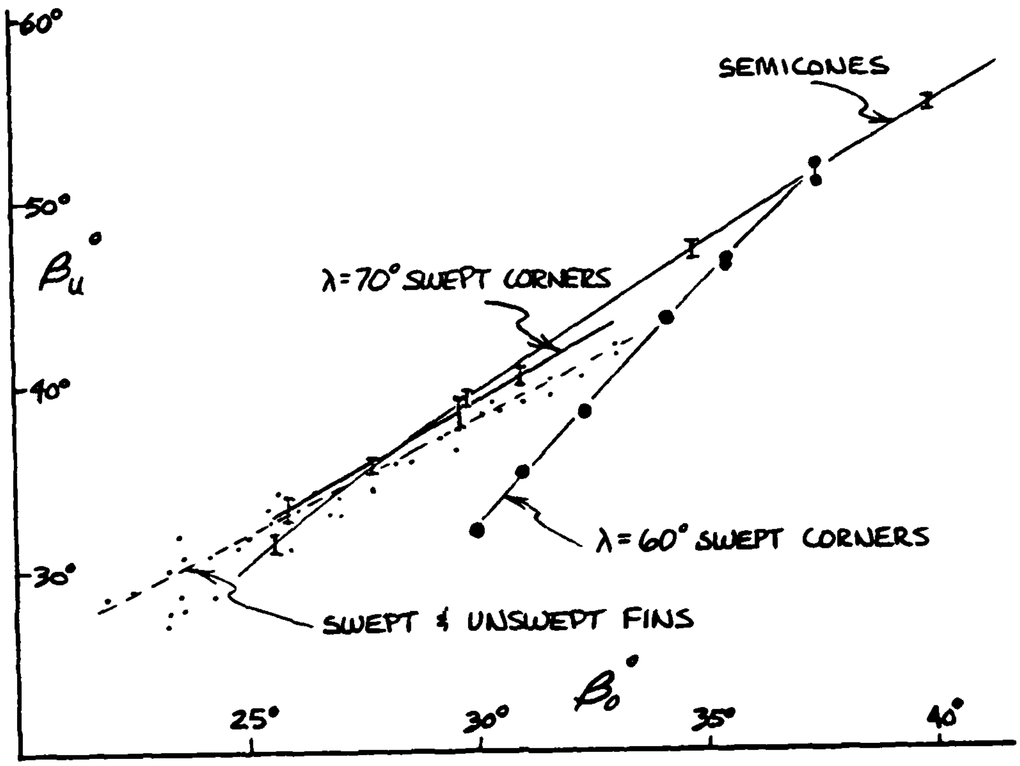


Fig. 18. Conical Similarity Comparison of Fin, Semicone, and Swept Corner Interactions in Terms of Upstream Influence-Line Angle β_u as a Function of Incident Shock Angle β_o, M_∞ = 2.95.

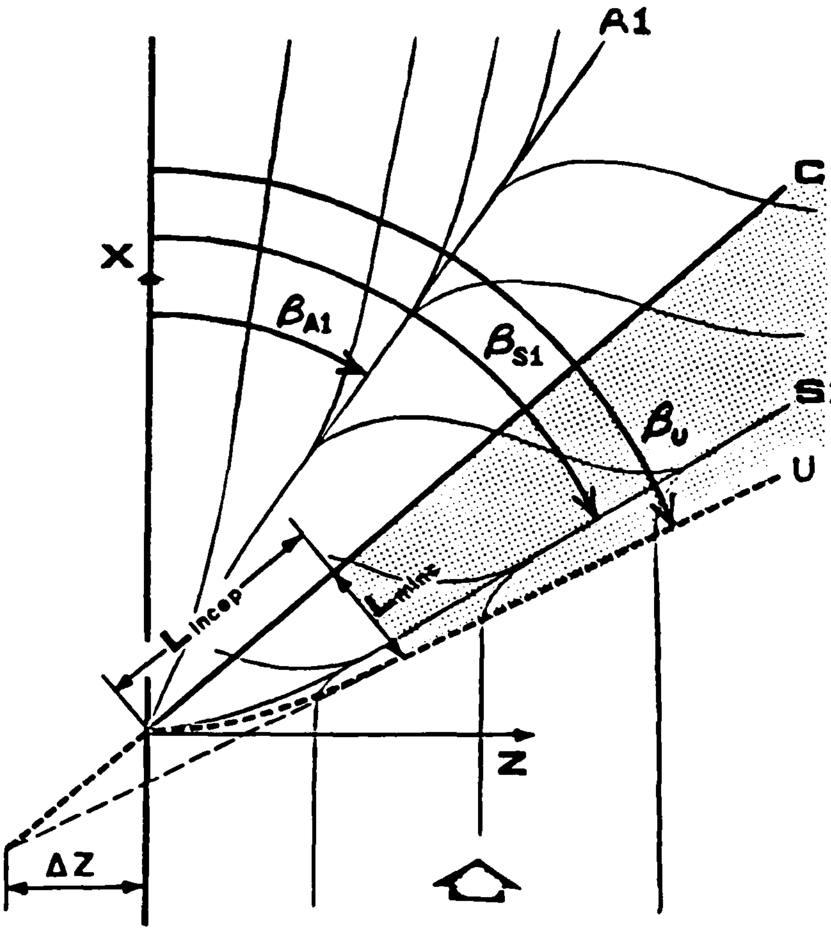


Fig. 19. Schematic Diagram of Conical Swept Corner Interaction Footprint Topography

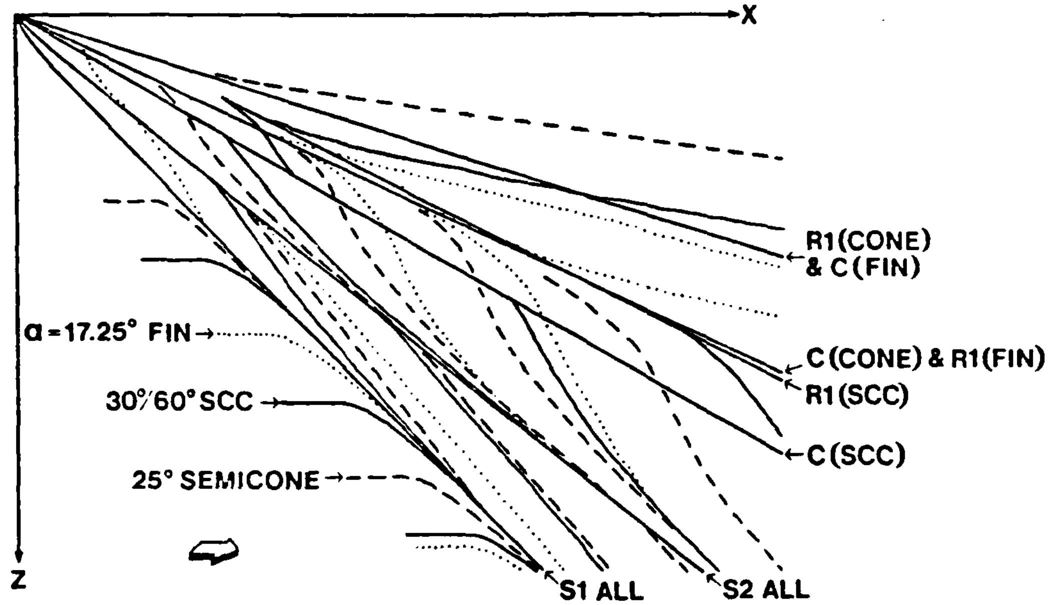


Fig. 20 - Comparison of Streakline Patterns of Similar Fin, Semicone, & Swept Compression Corner (SCC) Interactions.

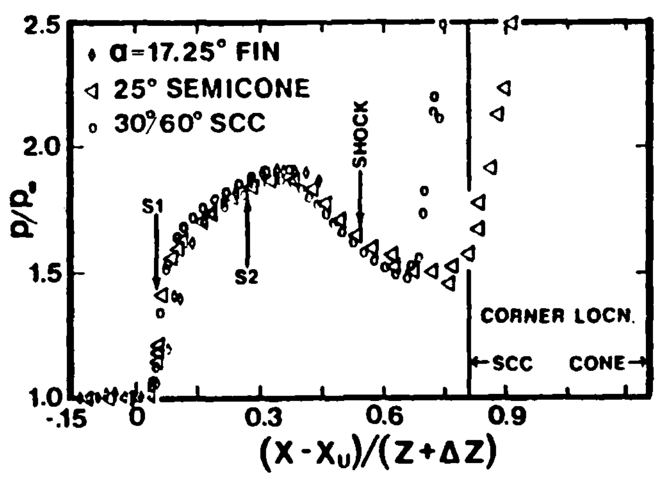


Fig. 21 - Free Interaction Surface Pressure Comparison.

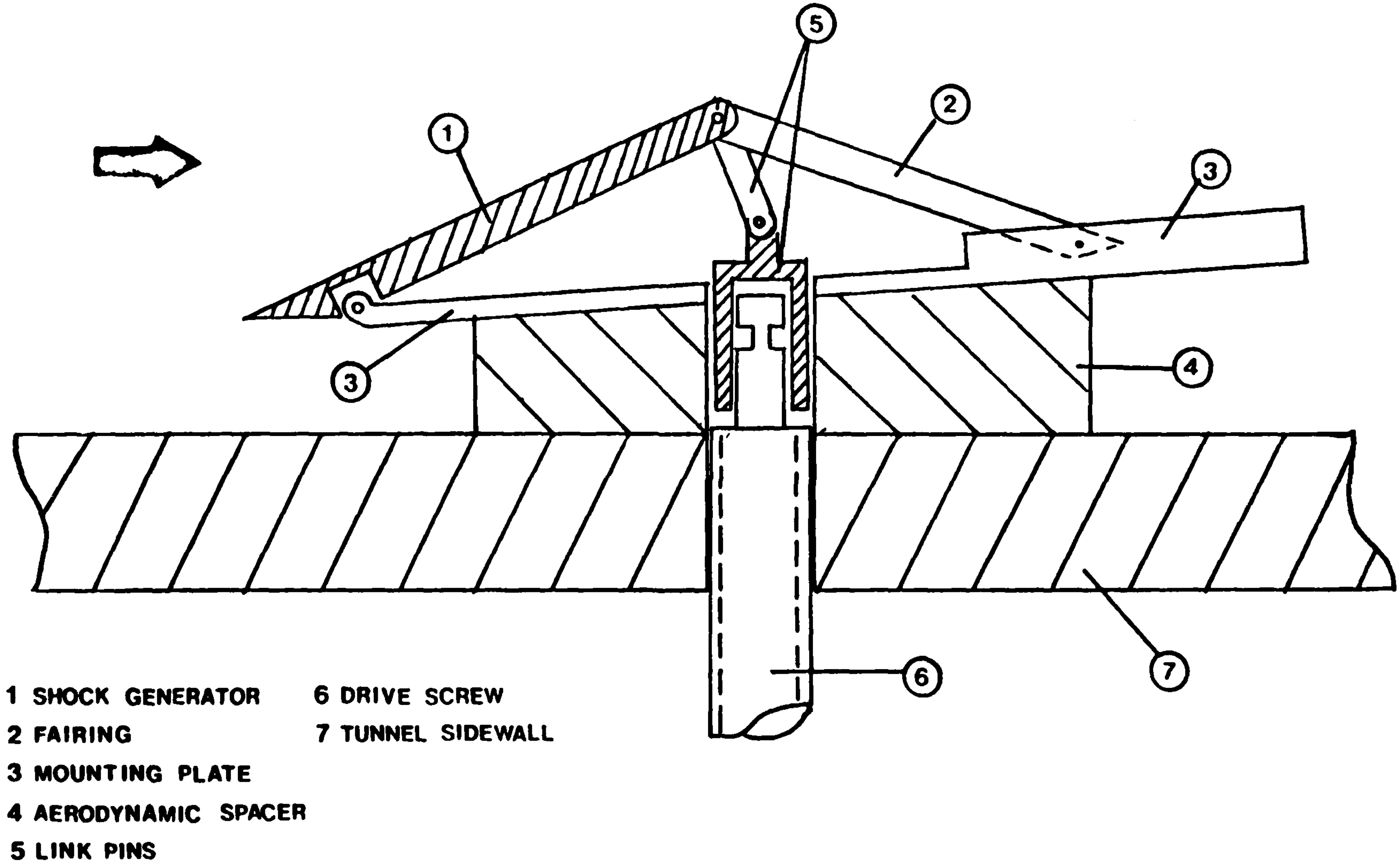


Figure 22. Plan View of Shock Generator Assembly.

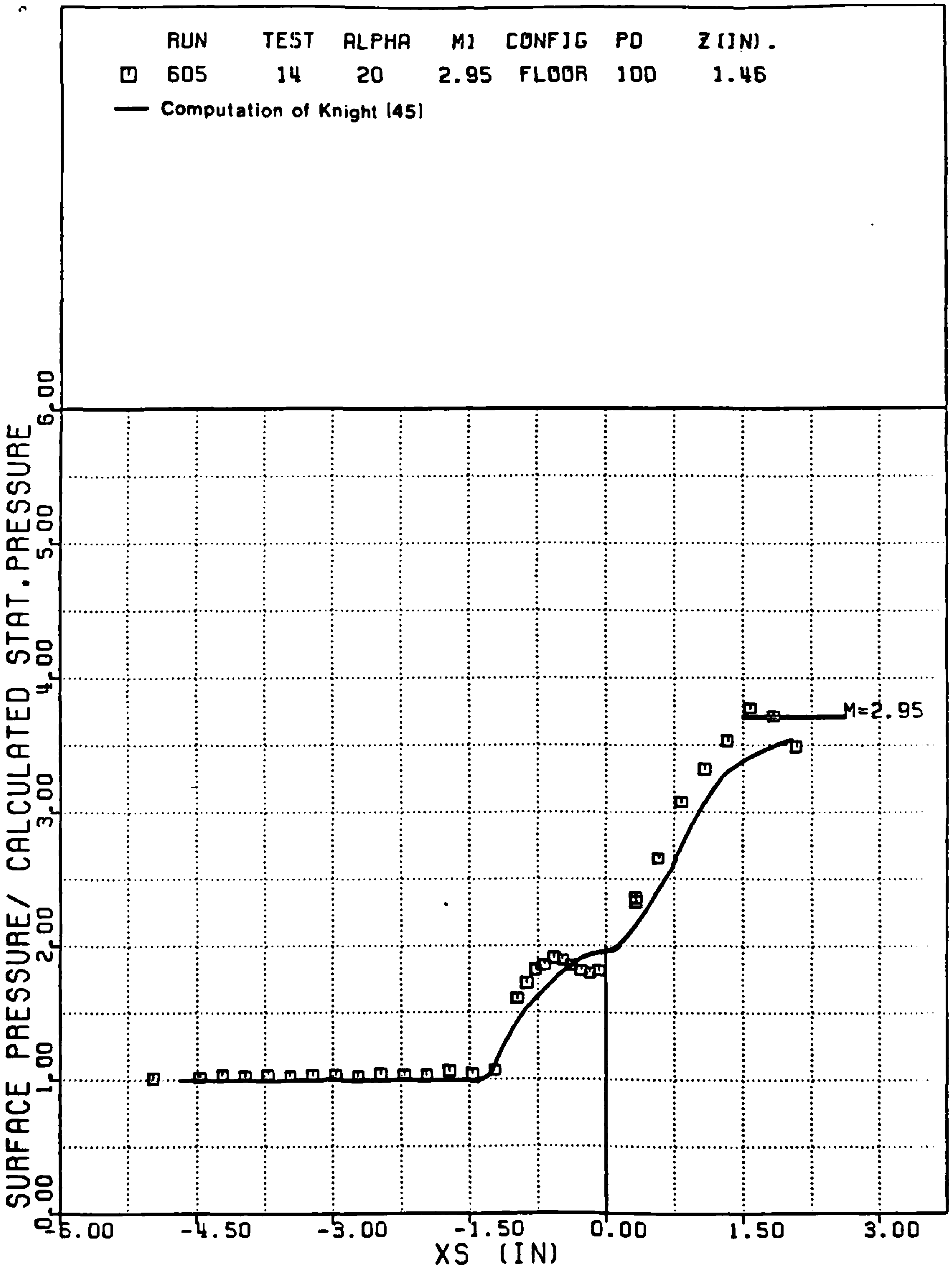


Figure 23. Comparison of a Surface Pressure Distribution with Computed Data of Knight

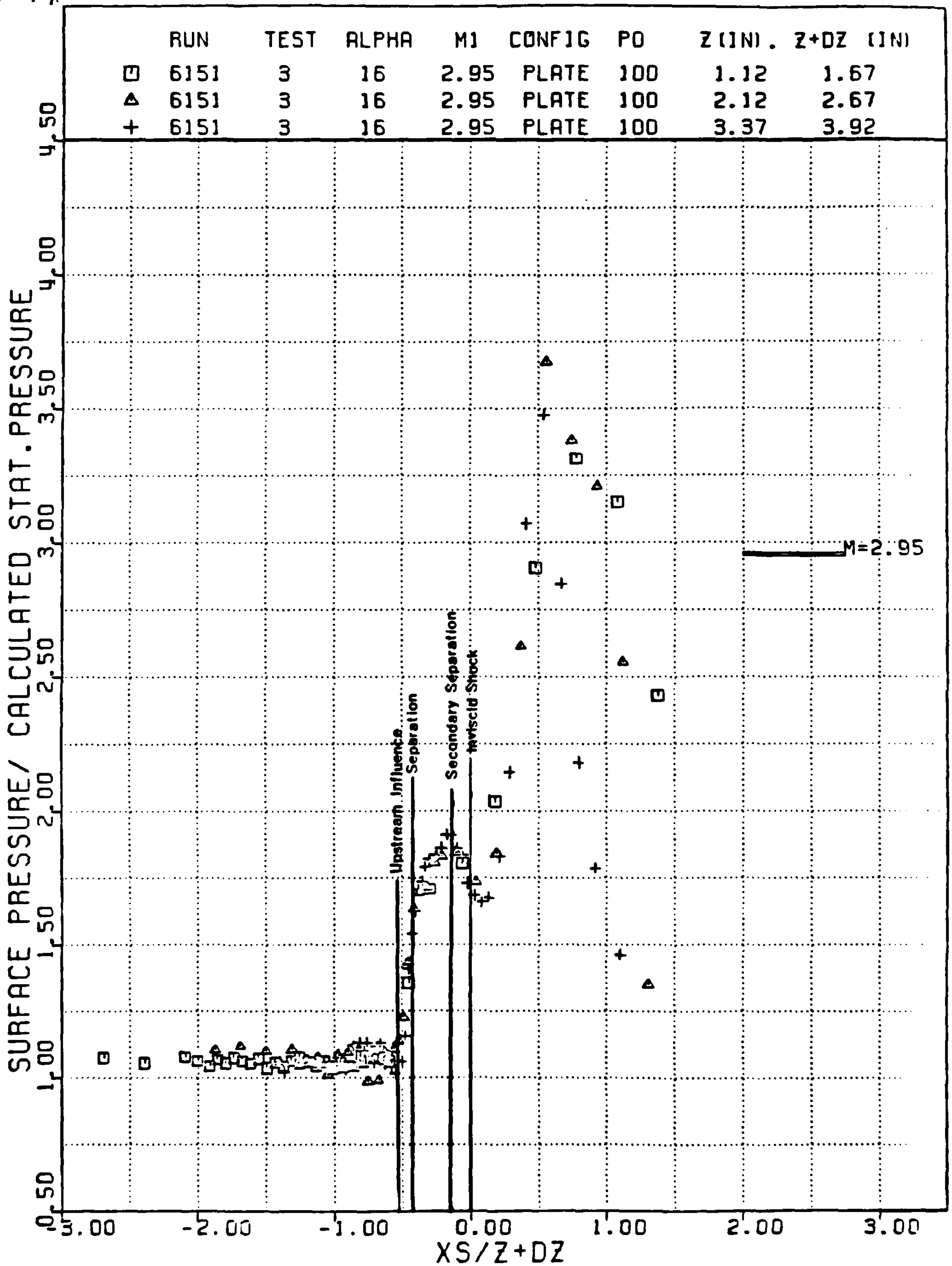


Figure 24. Typical Pressure Distribution/Kerosene-Lampblack Comparison Plot.

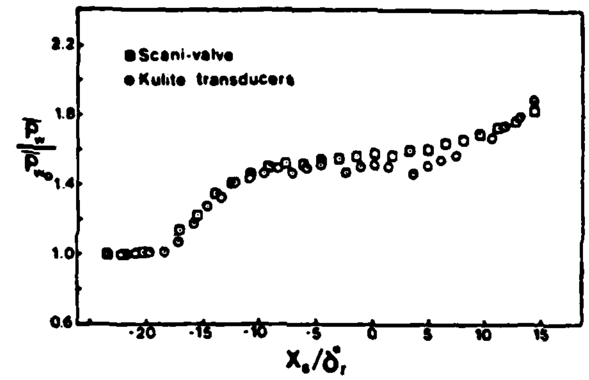


Fig. 25. Mean static pressure distribution alonc
Y = 95.3 mm.

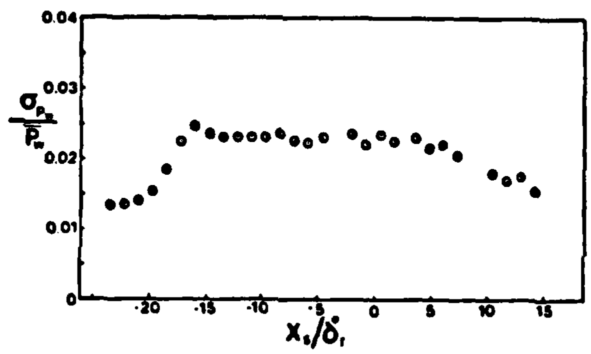


Fig. 26. RMS pressure fluctuations alonc
Y = 95.3 mm.